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Direct- and Alternating-Current Machine Design

Being Instructions for the Design of Motors and Generators

BY

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PREFACE.

This volume is especially prepared for self-instruction in the art of designing direct- and alternating-current machinery. Care has been taken to remain strictly within the province of design; the reader being assumed to possess knowledge of the principles of electricity and magnetism, and to be familiar with the theory of operation of electrical machines. The designs are carried out according to methods developed in actual practice and are supplemented by data and dimensions of lines of machines actually built by several of the largest American and European companies. The book is divided into two parts: one treating the design of direct-current machines, and the other that of alternating-current machines; each part being followed by a list of questions which clearly bring out the important points to be remembered.

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PART I.

Design of Direct-Current Dynamos and Motors

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SYMBOLS

USED IN DYNAMO CALCULATION.

The following is a list of the principal symbols used in connection with dynamo calculations:

AT = Total number of ampere turns.
at_a = Ampere turns required for armature core.
at_g = “ “ “ “ air gaps.
at_m = “ “ “ “ magnet frame.
at_r = “ “ “ “ armature reaction.

B_a = Radial thickness of armature core.
$\mathbf{B}_a$ = Magnetic flux density in armature core.
$\mathbf{B}_g$ = “ “ “ “ air gaps (field density).
$\mathbf{B}_m$ = “ “ “ “ magnet frame.

C = Current.
c = Circumferential current density.
$C.\ M.$ = Circular mils.

D_a = Diameter of armature core.
d_a = “ “ “ conductor.
D_m = “ “ magnet core.
d_m = “ “ “ wire.

E = E. M. F. of armature.
E' = Counter E. M. F. of motor.
Eff = Efficiency.
ε = Factor of eddy current loss in armature.

f = Frequency.
Φ = Flux.

h_a = Height of winding space on armature (depth of slot).
$H.\ P.$ = Horse-power.
η = Factor of hysteresis loss in armature.

$K.\ W.$ = Capacity of dynamo in kilowatts.
k = Percentage of power loss in armature.

L_a = Length of armature core.
l_a = “ “ active armature conductor.
l_A = Total length of armature conductor.
L_m = Length of magnet core.
l_m = “ “ “ wire.
L_M = “ “ magnetic circuit.
l_t = “ “ mean turn of wire on magnets.
λ = Factor of magnetic leakage.

M = Mass of iron in armature core.
m = Ratio of length to diameter of armature core.
m' = “ “ radial thickness to diameter of armature core.

N = Number of inductors on armature.
n = “ “ revolutions per second.
n_1 = “ “ “ “ minute.
n_P = “ “ pairs of magnet poles.
n_p = “ “ “ “ parallel armature circuits.

R_a = Total resistance of armature wire.
r_a = Resistance of armature winding, cold.
r_a' = “ “ “ “ warm.
ρ = Specific resistance of wire (ohms per foot).

S_a = Cooling surface of armature.
S_m = Cross-section of magnet frame.
S_w = Total area of winding space on armature.
S_w' = Available area of winding space on armature.
s = Specific cooling surface of armature.

v = Peripheral velocity of armature.

W = Capacity of dynamo, in watts.
w_a = Watts consumed in armature winding.
w_e = “ “ by eddy currents.
w_h = “ “ “ hysteresis.
wt = Weight, in pounds.

THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS

INTRODUCTION.

1. Branches of Science Involved in Dynamo Design.—The following discussion of the design of dynamos and motors will be confined to the consideration of direct-current machines.

The design of a dynamo and motor relates to three essential parts: first, the *armature* carrying the conductors in which the electric energy is generated or absorbed; second, the *field magnet* that produces the magnetic field or flux in which the armature revolves; and third, the various *mechanical parts* and arrangements necessary to carry out the electrical and magnetic actions. Thus, three great branches of science—*electricity*, *magnetism*, and *mechanics*—are involved.

2. General Method to be Followed.—In taking up the design of a dynamo or motor, the mind should not be allowed to jump at conclusions or immediately settle upon some particular solution of the problem. The question should be considered from all points of view before any one point is decided. One should also endeavor to be free from prejudices and not blindly follow custom. On the other hand, it is a mistake to attempt radical or sensational departures from well-established practice. By always striving for simplicity and directness, the latter danger is generally avoided.

Certain quantities entering the calculations are not prescribed and must be *assumed* by the designer. If he is experienced, usually the first or second assumption of the variable quantities will lead to a satisfactory result.

The beginner, however, will generally be so wide of the mark that numerous recalculations are necessary to learn the effect of the different variable quantities upon the result, and to arrive at a successful solution. The more trials that are made intelligently in this way, the more information is gained by the student. It is not wise, however, to carry out preliminary calculations elaborately, because it wastes time and is discouraging if they are found to be incorrect. One should have the moral courage to change or discard drawings and results when they are not right.

It is a common mistake to trust blindly to formulas which are merely shorthand, and, unless they are thoroughly understood, are very likely to give wrong results. Each quantity should be carefully scrutinized to make sure of its significance and relation to the other factors involved.

3. Parts of a Dynamo or Motor.—The chief parts of these machines are the *armature* and the *field magnet*. The latter is usually stationary, and is combined with the base and bearings to form what is called the *frame* of the machine. In alternating current machines it is quite common to have the field magnet revolve and the armature stationary. This arrangement is very rarely attempted in direct-current dynamos or motors, because it necessitates the rotation of the brushes and renders their adjustment extremely difficult.

It is better to consider the armature first, because it is the most important element of the machine, and the other parts should be made to conform to it. As a matter of fact, any part will have to be considered with reference to the others, but it is necessary to take up one at a time, and usually to go back and modify the first ones after the others have been evolved.

4. Forms in which the Problem presents Itself.—In most cases the object of designing a dynamo or motor is to produce a machine which will fulfill certain specified conditions.

A *generator* is usually required to develop either a given current, C amperes, or a certain electrical power, $K.W.$ kilowatts, at a given voltage, E, and at a prescribed speed, n_1 revolutions per minute. The value of the current, if the problem is given in the latter form, may be found by dividing the output, in watts, by the $E.\ M.\ F.$, in volts; or in symbols:

$$C = \frac{1{,}000\ K.\ W.}{E} \qquad (1)$$

where C = current, in amperes;
$K.\ W.$ = electrical power, in kilowatts;
E = E. M. F., in volts.

A *motor* is ordinarily designed to develop a given number of mechanical horse powers, $H.\ P.$, at a certain speed, n_1 revolutions per minute, when supplied by a given voltage, E.

5. Method of Motor Calculation.—In order to enable a motor problem to be treated in the same manner as the design of a generator, the H. P. may be converted into K. W. by multiplying the former by .746; and the counter E. M. F., E', of the motor may be assumed to be from *1* to *5* per cent. less than the supply voltage, E, depending upon the size and type of the motor. The difference between E and E' is usually between *1* and *2* per cent. for large machines of *100 H. P.* and more, and about *4* or *5* per cent. for small machines of *1* and *2 H. P.* If the speed of the motor is abnormally low, to enable it to be directly connected to printing presses, blowers, etc., the difference between the direct and counter E. M. F. is correspondingly greater. The following values, therefore, enable a motor to be treated the same as if it were a problem in dynamo design:

Output: $K.W. = .746\ H.P.$ (2)
Counter E. M. F.: $E' = .95\ E$ to $.99\ E$ (3)
Current: $C = \frac{746 \times H.\ P.}{E \times Eff.}$ (4)

In (**4**) the average values of the *electrical* efficiency of motors given in Table **1** may be used:

TABLE 1.

EFFICIENCIES OF MOTORS.

Size of Motor.	Average Electrical Efficiency.	Average Commercial or Total Efficiency.
½ H. P.	.90	.75
1 "	.92	.80
5 "	.94	.85
10 "	.95	.87
20 "	.96	.88
50 "	.97	.91
100 "	.98	.92
200 "	.98	.93
500 "	.985	.94
1000 "	.985	.95

In Table **1** the average values of the *commercial* or *total* efficiencies of motors of various sizes are added for comparison and reference.

It is possible to design a motor in terms of H. P., torque, etc., instead of K. W., current, etc., but the advantage of using the same formulas for both kinds of machines warrants the adoption of the above method. Any errors in assuming E' or the efficiency are not likely to be more than a few per cent., and can be subsequently corrected.

6. Forms of Armature.—The four principal types of armature—*ring, drum, pole,* and *disc*—have already been described in previous lessons. At the present time, only the first two forms are important, the pole armature not being used except in small toy motors or dynamos, and the disc armature being adopted in but a single type of direct-current machine—the *Desroziers* dynamo made in France.

The chief advantage of the ring armature lies in the fact that the coils which differ considerably in potential are widely separated from one another. For this reason the ring armature is preferable for very high voltage machines, such, for example, as series arc lighting generators. Formerly the ring armature had the advantage over the drum that single coils could be taken off and replaced without disturbing the rest of the winding; but the general use of *formed* coils for drum armatures, which is now the common practice, enables the same thing to be done in their case with almost equal convenience.

The great advantage of the drum form is due to the fact that it can be directly and securely mounted upon the shaft. In some cases armature cores are carried upon spiders, so that they may be wound in either the ring or drum fashion as desired. The latest practice seems to tend toward the adoption of the drum in preference to the ring type for small and medium size machines. This matter will be understood more clearly when the details of form and construction have been more fully considered.

7. Armature Cores.—If the core of the armature were made of one solid piece of iron, currents would be set up in it, since the outer portions of the core cut magnetic lines, exactly as the armature conductors themselves. The useless currents thus generated, called *Foucault* or *eddy* currents, consequently flow in the same direction as the armature currents, that is to say, ordinarily in a direction parallel to the shaft of the armature. In order to prevent these eddy currents, which consume power and also cause heat, from flowing, it is, therefore, necessary to intercept their path by subdividing, or **laminating,** the core perpendicularly to the shaft.

The usual plan is to build up the core of discs or rings of sheet iron, lightly insulated from one another, so that the magnetic lines can pass freely through each disc, but the eddy currents which tend to flow perpendicularly across the discs are stopped by the insulation between the latter. Since the eddy currents tend to flow in the same direction as the useful currents in the conductors, the core should always be laminated parallel to the lines of force and to the direction of the motion.

8. Wire Cores.—Iron *wire* has been employed for armature cores, and possesses the advantage of very complete subdivision and of being easily wound in a ring or drum of any desired size or form. A wire core has, however, the disadvantages of promoting magnetic discontinuity, of constituting a poor mechanical construction, and of entailing loss of space between the wires, especially if they are of circular cross-section.

9. Core Discs.—Discs or rings are almost always used for armature cores, and are punched or cut out of the softest sheet iron or mild steel, a special quality being manufactured for this purpose. The thickness is usually from .01 to .03 inch, a standard size being .022 inch. The same thickness is often employed for all sizes of machines, including the largest as well as the smallest, being adopted because it is convenient to handle and to punch, and is sufficiently thin to reduce the eddy currents to a small value.

For armatures less than about 2 feet in diameter, each core disc is a complete ring in one piece, but armatures of larger diameter are built up of a number of sectors in order to facilitate their punching and handling.

10. Effective Cross-Section of Armature Core.—The laminæ were formerly insulated from each other by *tissue paper*, *paint*, *varnish*, or *rust*, but the usual practice at present is to simply rely upon the *oxide coating* on the surface of the discs.

An armature core composed of such sheets, and forced together by heavy hydraulic or screw pressure, is found to contain from 85 to 95 per cent. of its volume of iron, the rest being made up of insulation, scale, and small air spaces due to slight inequalities in the sheets; hence the effective cross-section or magnetic carrying capacity of such a core is from 15 to 5 per cent. less than that of an equal volume of solid iron of the same permeability.

The effective cross-section of the armature core is further reduced by the presence of ventilating spaces, or holes, which are often left in the armature core.

11. Advantages of Toothed Armatures.—In the **toothed** or **slotted** armature (Fig. 1), which is now largely superseding the **smooth** form, the conductors are wound in the slots between teeth or projections formed upon the main body of the core. This type, also called the *Pacinotti armature,* after its inventor, has the following advantages over the smooth core:

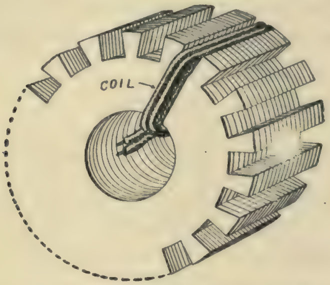


FIG. 1.—TOOTHED ARMATURE.

1. The reluctance of the air-gap is reduced to a minimum.
2. The armature conductors are protected from injury.
3. The conductors are firmly held in place and cannot slip on the core by the action of the electro-dynamic force exerted upon them.
4. Eddy currents in the armature inductors are avoided, since the magnetic lines snap across the latter instantly.*
5. If the teeth are practically saturated by the field magnetism, they oppose the shifting of the lines by *armature reaction.*

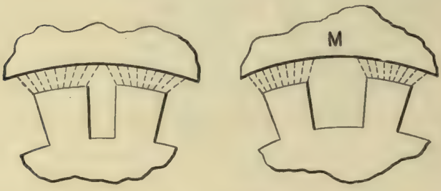
---

* This point will be considered further under the head of *Eddy currents in armature inductors.*

12. Disadvantages of Toothed Armatures.—The disadvantages of the toothed armature core are:—

1. It is somewhat more expensive to make.
2. The teeth tend to generate eddy currents in the pole-pieces.
3. The self-induction of the armature coils is increased.

The second difficulty can be practically overcome by making the distance between the teeth at their ends not more than 2 to 3 times the air-gap, so that the lines can spread from the corners of the teeth, and become nearly uniform on the pole-faces, as represented in Fig. 2. If the slots near the periphery are wider than three times the length of the air-gap, as shown in Fig. 3, there will be spaces, *M*, on the pole-pieces, where there are practically no lines.



Figs. 2 and 3.—Distribution of Magnetic Lines on Pole-Face with Toothed Armature, under Varying Conditions.

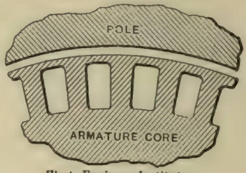


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Fig. 4.—Perforated Armature.

These spaces will move across the pole-faces, and the shifting field thus produced tends to induce eddy currents in the pole-pieces, which should in such cases be laminated or grooved in the direction of motion of the armature, in order to reduce the flow of these wasteful currents. In some cases the entire armature has been covered with a thin layer of iron wire, producing a continuous magnetic surface. The same effect is obtained by perforating the edge of the armature core, as shown in Fig. 4, instead of having open slots. The objections to both of these latter forms are their increased self-induction and the fact that a certain magnetic leakage occurs through the iron outside of the inductors.

PRELIMINARY CALCULATION OF ARMATURE.

13. Preliminary Determination of Dimensions of the Armature.

13. Preliminary Determination of Dimensions of the Armature.—There is no absolute rule for determining the size of an armature, since it depends upon many conditions which cannot be included in a formula or covered in any general way; nevertheless there are several facts that will aid us in assuming an approximate size, which can be modified later if found incorrect. In point of fact, as already stated in the introduction, it is almost an advantage if several different sizes are tried before arriving at the right one, since it gives a broader view of the question and enables one to choose finally the best size, all things considered.

The chief points to consider in arriving at the size of an armature are: 1. *Peripheral speed.* 2. *Cooling surface.* 3. *Space for inductors.* 4. *Surface covered by pole-pieces.*

14. Peripheral Speed of Armature.—One guide in obtaining the diameter of an armature is the fact that the peripheral velocity, v, must be kept within the limits established by practice, that is, between *1,500* and *6,000* feet per minute, *3,000* being a common value. Since the peripheral velocity of an armature may be expressed as the product of the armature circumference, in feet, by the number of revolutions per minute, or

$$v = \frac{D_a \pi}{12} \times n_1, \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

the approximate diameter, D_a, of the armature, in inches, can be found by the following equation, when n_1, the number of revolutions per minute, is known:

$$D_a = \frac{12v}{\pi n_1} = 3.8 \times \frac{v}{n_1} \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The value of v in (**6**) should be taken within the limits given in Table **2**, according to the kind of machine.

TABLE 2.

ARMATURE SPEEDS FOR VARIOUS KINDS OF DYNAMOS.

Kind of Machine.	Peripheral Velocity, in feet per minute.	
	Usual Limits.	Average.
High-Speed Ring Machine	3,000 to 6,000	4,500
Medium-Speed Ring Machine	2,000 " 4,000	3 000
Drum-Armature Machine	2,000 " 4,000	3,000
Low-Speed Direct-Driven Machine	1,500 " 3,000	2,250

The lower limit in all cases refers to small dynamos, while the upper limit refers to large machines, the average in each instance corresponding to a size of about *100 K. W.* For machines below that size, therefore, use a value smaller than the average, and for machines above *100 K. W.* take a value between the average and the upper limit. The general average of *3,000* feet per minute is a good practical value for *belt-driven drum armatures* of from *10* to *300 K. W.* capacity, and for *direct-driven machines* of from *500 K. W.* output up; while for *high-speed ring armatures* it applies only to sizes smaller than ½ *K. W.*

15. Approximate Cooling Surface of Armature.—Another method of predetermining the size of an armature is based upon the surface required to dissipate the heat generated within the armature. There is some uncertainty as to what surface we are to consider the cooling surface of an armature.

For a *drum armature* we will here take it to be the sum of the cylindrical surface of the armature core and of the area of a circle the diameter of which is the external diameter of the core, or

$$S_a = D_a \pi L_a + D_a^2 \frac{\pi}{4}, \quad \text{.............}(7)$$

where D_a is the diameter, and L_a the length of the armature core. In a drum armature, then, only one of the two end surfaces *A, B*, Fig. 5, is taken into account, which is done for the reason that the surface *B*, which is near the commutator *C*, receives heat from the latter by radiation and convection as well as by conduction through the armature conductors. It is, therefore, wise to consider this surface, *B*, as part of the cooling surface of the commutator, which is usually the hottest part of the machine.

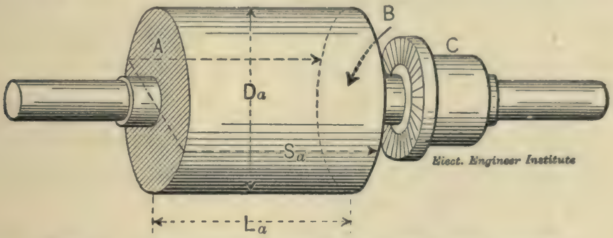

FIG. 5.—COOLING SURFACE OF DRUM ARMATURE.

Expressing in the above formula (7) the length L_a as a multiple, or ratio, of the diameter, or $L_a = mD_a$, where m is this shape-ratio of the armature, the approximate cooling surface of a drum armature can be expressed as:

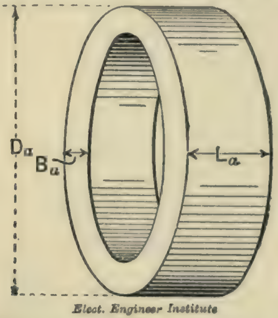

FIG. 6.—COOLING SURFACE OF RING ARMATURE.

$$S_a = D_a\pi m D_a + D_a^2\frac{\pi}{4} = D_a^2\pi(m + \tfrac{1}{4}), \dots\dots\dots\dots (8)$$

which contains only the diameter and the shape-ratio.

In the case of a modern *ring armature*, usually the total core surface is open to the access of air; hence, the entire core surface can in most cases be considered as cooling surface. If, however, the construction of the armature is such that the inner surface or one of the end surfaces is covered up, the area so covered must be excluded from the calculation of the cooling surface. The total surface of a ring having a diameter D_a, a length L_a, and a radial depth B_a, Fig. 6, is given by the formula:

$$S_a = (D_a - B_a)\pi \times 2(L_a + B_a) \ldots\ldots\ldots \textbf{(9)}$$

Expressing both the length and the radial thickness of the ring as multiples of its diameter, $L_a = mD_a$ and $B_a = m'D_a$, we obtain:

$$S_a = 2\pi \times (D_a - m'D_a) \times (mD_a + m'D_a)$$
$$= 2\pi \times D_a^2 \times (1 - m') \times (m + m') \ldots\ldots \textbf{(10)}$$

16. Determination of Armature Diameter by Cooling Surface.—It is found that from ½ to 1 square inch of cooling surface is needed to liberate the heat resulting from each watt of power lost in the armature. This includes not only the copper, or C^2R, loss due to the resistance of the armature winding, but also the iron loss, or core loss, due to hysteresis and eddy currents. These losses are not definitely known in the beginning, but it is reasonable to assume that they will be from *1* to *3* per cent. of the total power in large machines of *500 K. W.* and over; *3* to *5* per cent. for machines of about *100 K. W.;* *4* to *6* per cent. for sizes of about *50 K. W.;* *5* to *8* per cent. for *10 K. W.;* *6* to *10* per cent. for *5 K. W.;* *8* to *12* per cent. for *1 K. W.;* and up to *20* and even *25* per cent. for *very small* machines, such as battery motors, etc.

The cooling surface, in square inches, required in any case is, therefore:

$$S_a = s \times k \times W, \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(11)}$$

in which W = capacity of dynamo, in watts;
s = specific cooling surface,
= *.5* to *1* square inch per watt of power loss;
and k = percentage of power loss in armature (see Table **3** for average values).

TABLE 3.

POWER LOSS IN ARMATURES OF VARIOUS SIZES.

Size of Machine.	Percentage of Power Loss, *k*.	
	Usual Limits.	Average.
Above 500 K. W	.01 to .03	.02
Between 500 and 100 " "	.02 " .05	.035
" 100 " 50 " "	.03 " .06	.045
" 50 " 10 " "	.04 " .08	.06
" 10 " 5 " "	.05 " .10	.075
" 5 " 1 " "	.06 " .12	.09
Below 1 " "	.10 " .20	.15

Substituting in formulas (**8**) and (**10**) the value of S_a given in formula (**11**), we obtain:

for drum armatures: $D_a^2\pi(m+\frac{1}{4})=s\times k\times W$, or

$$D_a=\sqrt{\frac{s\times k\times W}{\pi(m+\frac{1}{4})}};\ldots\ldots\ldots\ldots(\mathbf{12})$$

for ring armatures: $2\pi D_a^2(1-m')\,(m+m')=s\times k\times W$, or

$$D_a=\sqrt{\frac{s\times k\times W}{2\pi(1-m')\,(m+m')}}\ldots\ldots(\mathbf{13})$$

Since in formula (**12**) one of the end surfaces is neglected, whereas in (**13**) the entire core surface is considered as cooling surface, the actual cooling surface of a drum armature is larger than that given by (**8**), while the effective cooling surface of the ring armature is smaller than the value found by (**10**). Consequently, in order to reduce both formulas to the respective actual cooling surface, it is necessary to take a somewhat larger value of *s* for a ring armature than for a drum, in spite of the fact that the former, owing to its better ventilation, will require less cooling surface than the latter in order to dissipate equal amounts of heat. The student should use $s = .5$ to $.75$ in (**12**) for *drum* armatures, and $s = .75$ to *1* in (**13**) for *ring* armatures.

In practice the shape-ratios m or m' in the above formulas are usually known from previous designs of the same type; but if their approximate values are not given in this manner, a number of assumptions of m and m' may be made within the limits compiled in the following Table **4**:

TABLE 4.

SHAPE-RATIOS FOR DIFFERENT ARMATURES.

Kind and Size of Armature.	Ratio m of Length to Diameter.	Ratio m' of Radial Thickness to Diameter.
Ring, above 100″ Diameter....	.15 to .25	.05 to .10
Ring, from 100″ to 20″ Diameter........................	.25 " .5	.08 " .25
Ring, below 40″ Diameter ..	.25 " 1.	.10 " .30
Drum, above 30″ "	.75 " 1.5	—
Drum, from 10″ to 30″ Diameter	.75 " 1.75	—
Drum, below 10″ Diameter....	1. " 2.	—

A comparison of the value calculated from (**12**), or (**13**), respectively, with that previously obtained from (**6**), will assist the designer in deciding upon the final diameter of the armature. The student, who naturally lacks the experience of a professional designer, should also consult the dimensions of existing machines of similar output and speed, tables of which are given in Par. **19**.

17. Example of Drum Armature.—*Find the approximate diameter of a drum armature for a* **50 K. W.** *belt-driven generator to run at* **500** *revolutions per minute.*

Solution.—Taking the value of *3,000* for the peripheral velocity. in accordance with Par. **14,** we have from formula (**6**):

$$D_a = 3.8 \times \frac{3000}{500} = \mathbf{22.8} \text{ inches.}$$

According to Table **3,** the percentage of power loss in the armature of a 50 K. W. dynamo ranges between .04 and .08; a good value for a high-class machine therefore, is $k = .06$. The specific cooling surface, according to formula (**11**), can be taken between .5 and 1 square inch per watt; using the average value, we have $s = .75$. For a drum armature of the above found diameter. a good shape-ratio is $m = 1.2$ (see Table **4,** page 14); hence, the approximate diameter of the armature, from formula (**12**):

$$D_a = \sqrt{\frac{.75 \times .06 \times 50.000}{3.1416 \times (1.2 + \frac{1}{4})}} = \sqrt{\frac{2250}{4.5553}} = \mathbf{22.2} \text{ ins.}$$

This being practically the same as the value obtained above from formula (**6**), the nearest even value between the two results, or $D_a = \mathbf{22\frac{1}{2}''}$, may be decided upon.

18. Example of Ring Armature.—*Compute the diameter of a ring armature for a* **200 K. W.** *direct-driven generator which is to run at* **175** *revolutions per minute.*

Solution.—The peripheral velocity should in this case be taken $v = 2.250$ feet per minute (see Table **2,** page 10); hence, we have by (**6**):

$$D_a = 3.8 \times \frac{2250}{175} = \mathbf{48.8} \text{ inches.}$$

For the case in hand, the specific cooling surface should be taken between .75 and 1; let us assume $s = .8$. The percentage of power loss in the armature of a direct-driven 200 K. W. dynamo is about 4 per cent.; hence, $k = .04$. From Table **4,** the average ratio of length to diameter in this case is $m = .375$, and the average ratio of radial breadth to diameter is about $m' = .15$. Inserting these values into (**13**), we have:

$$D_a = \sqrt{\frac{.8 \times .04 \times 200,000}{6.2832 \times (1 - .15) \times (.375 + .15)}} = \sqrt{\frac{6400}{2.8}} = \mathbf{47.8} \text{ ins.}$$

The diameter required to give an adequate cooling surface being somewhat smaller than that for which the peripheral velocity is just right, a value between the two results obtained may be taken. Their average is about

$$D_a = 48\tfrac{1}{2} \text{ inches.}$$

19. Tables of Dimensions of Modern Dynamos.—In order to guide the student in the selection of values for the various variable quantities which he has to assume in the course of a dynamo calculation, tables of dimensions of modern machines are here given, covering all the usual cases of dynamo design. The tables include drum as well as ring armature machines, and give the principal dimensions for high, medium, and low speeds, for all ordinary sizes. In Tables **5** to **10** the dimensions of some of the machines of the *Crocker-Wheeler*, *General Electric*, and *Westinghouse Companies* are compiled, and in Tables **11** and **12** the armature dimensions of all the machines contained in Tables **5** to **10** are tabulated according to size and speed, so as to be readily employed for reference.

In the case of an example calling for the design of a machine which is to run at a speed not sufficiently near any of the speeds given for that output in Tables **11** or **12**, a standard of comparison may be obtained by interpolating between the next higher and lower speeds found for the same output and type of armature. For instance, if a 200 K. W. ring-type dynamo is to be calculated for a speed of 300 revs. per min., the result of equations (**5**) and (**9**), or (**10**), respectively, should be compared with the diameter obtained by interpolating between the dimensions given in Table **11** for the 200 K. W. high-speed ring armature and the 200 K. W. medium-speed ring armature, thus:

Diameter, 200 K. W. ring armature, 450 revs per min. .... 32½ ins.
" 200 " " " 175 " " " .... 50 "
" 200 " " " 300 " " " by interpolation:

$$32\tfrac{1}{2} + \left[\frac{450 - 300}{450 - 175} \times \left(50 - 32\tfrac{1}{2}\right)\right] = 32\tfrac{1}{2} + 9\tfrac{1}{2} = \mathbf{42} \text{ inches.}$$

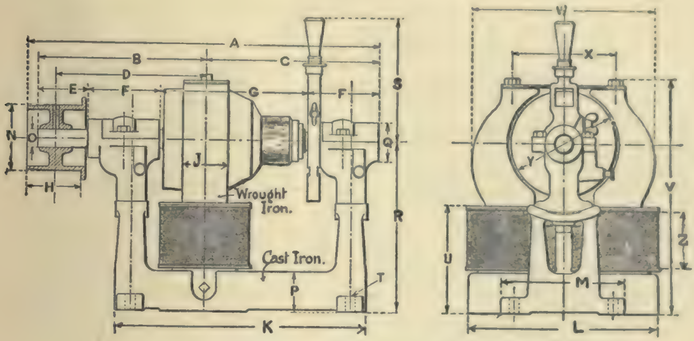

FIG. 7.—CROCKER-WHEELER BIPOLAR MOTOR.

TABLE 5.

DIMENSIONS OF CROCKER-WHEELER BIPOLAR MEDIUM-SPEED RING-ARMATURE MOTORS. (See Fig. 7.)

H. P.	K.W.	R. p. m.	Weight.	A	B	C	D	E	F	G	H	J	K	L
1/12	.1	1800	19	7 11/16	3 13/16	3 11/16	3	1 5/8	1 1/4	3 5/8	1	2	5 3/4	5 1/8
1/6	.15	1600	27	9 7/8	4 11/16	4 27/32	4 1/8	1 1/4	1 7/8	4 1/2	1	1 5/8	7 1/2	6 1/2
1/4	.25	1400	70	14 15/16	6 5/8	7 11/16	6 1/8	1 1/2	3 1/8	6 5/8	2 1/4	1 7/8	11 5/8	8 5/8
1/2	.5	1200	100	17 3/4	8 3/4	9 1/16	7 3/16	2 5/8	3 3/4	7 11/16	3	2 1/8	13 1/16	10
1	1.	1000	205	19 1/4	9 1/4	9 3/4	7 3/4	2 11/16	3 7/8	8 9/16	3 1/2	2 3/16	14 7/16	13 1/4
2	1.5	975	288	22 1/2	10 5/16	11 3/4	8 3/4	2 3/4	4 7/16	10 7/16	4	3 5/16	17 1/4	14 1/4
3	2.25	950	410	26 13/16	11 13/16	14 3/8	10 5/8	3 1/4	5	13 1/16	4 1/4	3 9/16	21 7/16	16 1/4
5	4.	925	510	28 3/16	12 31/32	14 13/16	10 7/8	3 25/32	5	14	5	4 13/16	22 3/8	19 1/4
7 1/2	6.5	875	760	33	15 1/16	16 15/16	13 1/16	4	5 3/4	16 1/2	6	5 5/8	26 1/4	21 1/4
10	8.5	850	920	36 1/4	17	18 1/2	14 1/4	5	6 1/2	17 1/2	7	6 1/4	28 1/2	23 3/16

H. P.	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1/12	3 1/2	1 1/2	3/8	1	9/16	5 11/16	..	1/4	3 15/16	7 7/8	5 1/8	3	3	2 3/4
1/6	4 1/2	1 1/2	3/8	1 7/16	1 3/16	6 1/8	..	5/16	4 1/16	8 1/2	5 7/16	3 3/8	3 19/32	2 1/2
1/4	4 9/16	3	9/16	1 7/8	1 1/2	7 3/4	..	3/8	4 15/16	10 11/16	8 1/4	4 5/8	4 3/4	2 7/8
1/2	6 5/8	3	11/16	2 1/8	2	9	7 13/32	1/2	5 3/4	12 9/16	9 1/8	5 1/2	5 3/8	3 1/2
1	8 3/4	4	7/8	2 13/16	2 1/4	10 5/8	7 13/32	1/2	6 3/4	15	12 7/16	7 1/4	7	3 5/8
2	9	5	1	3 3/16	2 3/8	11 1/16	7 3/4	1/2	6 7/8	15 3/4	13 3/4	8	7 3/4	3 1/2
3	11 1/2	6	1	2 9/16	2 5/8	11 13/16	9 5/8	5/8	7 3/8	18 3/4	13 1/2	7 1/2	8 1/4	4 3/8
5	12	7	1 1/8	3 3/8	2 5/8	13 3/8	9 5/8	5/8	8 1/2	21 3/8	15 1/4	7 1/2	9 3/16	4 3/8
7 1/2	14 1/4	8	1 1/4	4	3 1/8	14 5/8	10 3/8	5/8	9 1/4	23 1/2	17 7/8	7 1/2	10 1/8	4 3/4
10	15 3/4	9	1 1/2	4 1/4	3 1/2	16 1/4	11 1/2	5/8	10 3/16	25 3/4	19 3/16	8 3/4	11	5 1/2

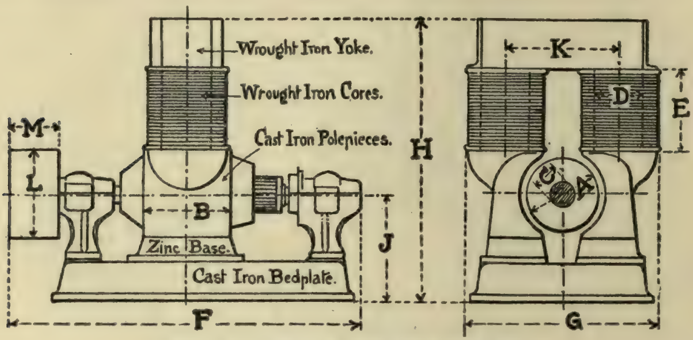

FIG. 8.—EDISON BIPOLAR DYNAMO.

TABLE 6.

DIMENSIONS OF EDISON BIPOLAR HIGH-SPEED DRUM-ARMATURE DYNAMOS AND MOTORS. (See Fig. 8.)

Generator.		Motor.		Weight.	Armature.			Magnets.		Frame.					Pulley.	
K. W.	R. p m.	H. P.	R. p. m.		A	B	C	D	E	F	G	H	J	K	L	M
.5	2400	.5	2100	90	$2\frac{5}{16}$	4	$\frac{11}{16}$	$2\frac{5}{8}$	$4\frac{1}{2}$	$16\frac{5}{8}$	$9\frac{1}{2}$	$12\frac{1}{2}$	$4\frac{5}{16}$	$4\frac{7}{8}$	$3\frac{1}{2}$	2
.75	2400	.75	2100	120	$2\frac{5}{8}$	5	$\frac{7}{8}$	$2\frac{3}{4}$	$5\frac{1}{2}$	$21\frac{1}{4}$	$9\frac{3}{4}$	$13\frac{3}{4}$	$4\frac{5}{16}$	$5\frac{1}{2}$	$3\frac{1}{2}$	$2\frac{1}{2}$
1.5	2100	1.5	1600	270	$3\frac{25}{32}$	$6\frac{1}{2}$	$\frac{15}{16}$	$3\frac{3}{4}$	$6\frac{3}{4}$	$24\frac{1}{4}$	$13\frac{1}{2}$	19	7	$7\frac{7}{16}$	4	3
3	1900	3	1450	550	$4\frac{1}{2}$	8	$1\frac{1}{8}$	5	$7\frac{5}{8}$	33	17	23	$8\frac{1}{2}$	$9\frac{1}{4}$	$7\frac{1}{2}$	3
6	1800	6	1350	830	$5\frac{11}{16}$	$9\frac{1}{4}$	$1\frac{3}{8}$	$5\frac{3}{4}$	$8\frac{3}{4}$	$38\frac{3}{4}$	20	$26\frac{7}{8}$	$10\frac{1}{16}$	11	8	4
8.5	1700	9	1325	1090	$5\frac{7}{8}$	10	$1\frac{5}{8}$	$6\frac{5}{16}$	$10\frac{5}{8}$	$44\frac{1}{8}$	22	$30\frac{1}{2}$	$11\frac{1}{8}$	12	$8\frac{1}{2}$	5
12	1600	14	1275	1470	$6\frac{1}{4}$	12	$1\frac{7}{8}$	$7\frac{3}{8}$	$12\frac{1}{4}$	$48\frac{3}{8}$	$23\frac{1}{2}$	34	$12\frac{1}{8}$	$12\frac{1}{4}$	9	6
15	1500	17.5	1150	2130	$6\frac{3}{4}$	$13\frac{1}{2}$	$2\frac{1}{4}$	$8\frac{1}{4}$	$13\frac{5}{8}$	57	$25\frac{3}{4}$	38	$13\frac{5}{8}$	$13\frac{7}{8}$	$11\frac{1}{4}$	8
20	1400	24	1100	2880	$7\frac{3}{4}$	15	$2\frac{1}{2}$	$9\frac{1}{4}$	$15\frac{1}{8}$	$65\frac{3}{4}$	$28\frac{3}{8}$	$41\frac{3}{4}$	$14\frac{5}{8}$	$15\frac{1}{8}$	12	9
25	1300	30	950	3570	$8\frac{3}{4}$	$16\frac{1}{2}$	3	$10\frac{1}{8}$	$16\frac{1}{4}$	$68\frac{1}{4}$	$30\frac{1}{4}$	$45\frac{1}{8}$	$15\frac{5}{8}$	$16\frac{1}{4}$	13	10
30	1200	36	880	4340	$9\frac{3}{16}$	18	$3\frac{1}{4}$	$11\frac{1}{8}$	$16\frac{7}{8}$	$73\frac{1}{2}$	$31\frac{3}{8}$	$47\frac{5}{8}$	$16\frac{1}{2}$	$16\frac{3}{8}$	14	11
45	1000	60	750	6800	$11\frac{1}{16}$	$20\frac{1}{2}$	$3\frac{3}{4}$	$12\frac{3}{4}$	$20\frac{1}{8}$	$83\frac{1}{2}$	36	$57\frac{1}{2}$	$19\frac{1}{2}$	$19\frac{3}{4}$	17	12
60	700	70	525	9790	$12\frac{7}{8}$	$24\frac{1}{2}$	4	$15\frac{1}{8}$	$23\frac{7}{8}$	$92\frac{1}{2}$	$40\frac{3}{4}$	$65\frac{7}{8}$	$21\frac{3}{4}$	$22\frac{1}{2}$	24	13
100	650	120	550	16200	$16\frac{3}{8}$	25	$4\frac{3}{4}$	$17\frac{1}{2}$	24	105	$47\frac{1}{2}$	$73\frac{1}{2}$	$24\frac{3}{4}$	$26\frac{1}{2}$	26	16
150	450	180	450	31790	$23\frac{3}{4}$	$26\frac{1}{2}$	6	$21\frac{1}{2}$	31	$119\frac{1}{8}$	$59\frac{1}{4}$	$92\frac{1}{2}$	$31\frac{3}{4}$	33	41	21
200	450	240	450	39000	$23\frac{3}{4}$	$34\frac{1}{4}$	$7\frac{3}{4}$	23	31	$135\frac{1}{2}$	$67\frac{3}{4}$	94	$31\frac{3}{4}$	$37\frac{3}{4}$	44	24

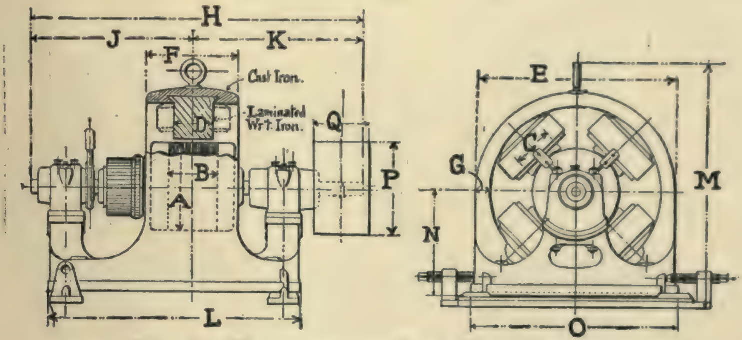

FIG. 9.—WESTINGHOUSE FOUR-POLE DYNAMO.

TABLE 7.

DIMENSIONS OF WESTINGHOUSE FOUR-POLE MEDIUM AND HIGH SPEED DRUM-ARMATURE DYNAMOS AND MOTORS. (See Fig. 9.)

Machine. No.	Medium Speed.			High Speed.			Weight.	Armature.			Magnets	
	K. W.	H. P.	R. p. m.	K. W.	H. P.	R. p. m.		A	B	Nbr. of Slots.	C	D
1	.56	¾	1300	.75	1	1900	190	5⅝	2⅝	31	2½	2⅛
2	1.5	2	1200	1.875	2½	1700	290	6⅛	3¼	31	3⅛	2½
3	2 62	3½	1050	3.75	5	1600	550	7¾	4⅝	47	4⅛	3⅛
4	3.75	5	950	5.62	7½	1350	740	8⅛	5¼	41	5	3⅞
5	5.62	7½	850	7.5	10	1250	940	9⅛	5⅛	47	5¼	4⅛
6	7 5	10	750	11.25	15	1150	1190	10⅛	6	47	5¾	5
7	11.25	15	650	15	20	1050	1550	11⅝	6¾	47	6⅝	5⅛
8	15	20	600	22.5	30	975	2460	13	8	47 & 71	7½	6¼
9	.....	...	....	30	40	950	2950	13⅞	8⅛	61	8¼	6⅞
10	22.5	30	575	37.5	50	900	3410	15	8⅛	41 & 61	8	7½
11	30	40	550	45	60	850	3900	15¾	8½	47 & 59	8	8
12	37.5	50	550	56.25	75	800	4300	16⅛	9	71 & 55	8½	8⅛

Machine. No.	Yoke.			General Dimensions.							Pulley.	
	E	F	G	H	J	K	L	M	N	O	P	Q
1	13⅝	5½	¾	22	11	11	16⅛	17¼	7½	14⅝	3½	2½
2	14¾	6⅛	1	26½	12⅞	13⅝	19⅞	18⅝	7⅝	15½	5	3
3	18	8⅛	1⅝	32	15¾	16¼	24⅛	22⅞	9⅝	19	6	4
4	19⅛	9⅛	1¼	36	16¾	19¼	26⅝	24⅝	10⅛	20½	8	5
5	21⅛	10	1½	38	18⅝	19⅜	28¼	26⅝	11⅛	22⅝	8	5
6	24	10⅛	2	40¾	19⅛	21⅝	30⅛	30	12⅛	25¼	9	6
7	26⅛	12	2¼	44½	20⅞	23⅝	32⅞	32⅛	13¾	27⅛	14	7
8	30¼	13⅛	2⅞	50¾	25⅛	25⅝	33⅝	36⅝	15⅝	31⅛	14	8
9	33	14	3¼	54½	25⅞	28⅝	39⅞	40	17	34⅛	15	11
10	34½	14½	3⅝	56½	26⅝	29⅞	42	41⅛	17⅜	36½	15	11
11	35⅞	14⅞	3$\frac{7}{16}$	65½	34⅞	30⅝	47¼	43⅝	18⅛	37⅛	20	11
12	37	15¼	3½	66	33¾	32¼	47⅞	44	19	38¼	20	11

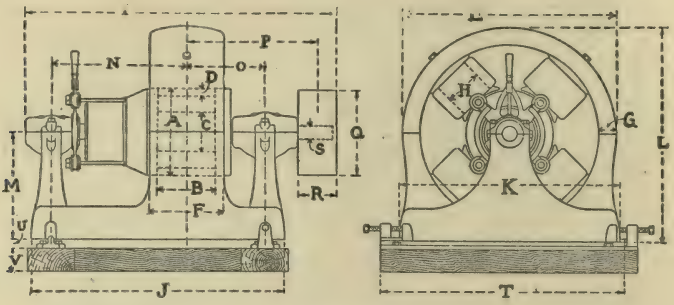

FIG. 10.—GENERAL ELECTRIC FOUR-POLE GENERATOR.

TABLE 8.

DIMENSIONS OF GENERAL ELECTRIC FOUR-POLE MODERATE AND HIGH SPEED RING-ARMATURE GENERATORS.

(See Fig. 10.)

No.	Medium Speed		High Speed.		Weight	Armature.					Magnet Frame.			
	K. W.	R.p.m.	K. W.	R p.m.	Lbs.	A	B	C	D	No. of Slots.	E	F	G	H
1	6.5	950	9	1450	970	9¼	6	4⅝	.834	46	23⅞	9	1 13/16	3 31/32
2	13.5	850	17 5	1175	1810	13	6½	6½	.804	52	31	12	2 3/16	5 7/32
3	20	700	30	1050	3200	16	7	7⅛	.918	66	37	15	3	6¾
4	30	675	45	975	4780	18	8¾	9¼	.944	116	44	16½	3⅜	7 5/16
5	50	600	65	875	6930	20¼	8¾	9 5/16	1 075	98	50	18	3¾	8 7/16
6	75	550	85	750	8560	22	9¼	10	1.208	96	54	19	4½	9⅛

No.	General Dimensions.								Pulley.			Rails.		Base
	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	38	31¾	26	24	12	16½	10¾	16⅛	11	4½	1⅜	34¾	1	3
2	49½	39	33	31	15½	19⅞	13⅛	21⅜	12½	8½	2	43½	1	3
3	60½	45½	40	37	18½	22¾	15¾	26¾	15	10½	2¼	52	1⅝	4
4	67¾	52¾	46½	44½	22½	26⅜	18⅜	29⅞	20½	11	2¾	55	1⅝	4
5	78⅝	57⅝	53	50	25	29¾	18⅞	33⅛	23	18½	3¼	62¾	1¾	6
6	92	63½	56	54	27	31¼	19¾	39	25	24½	3⅞	65½	2	6

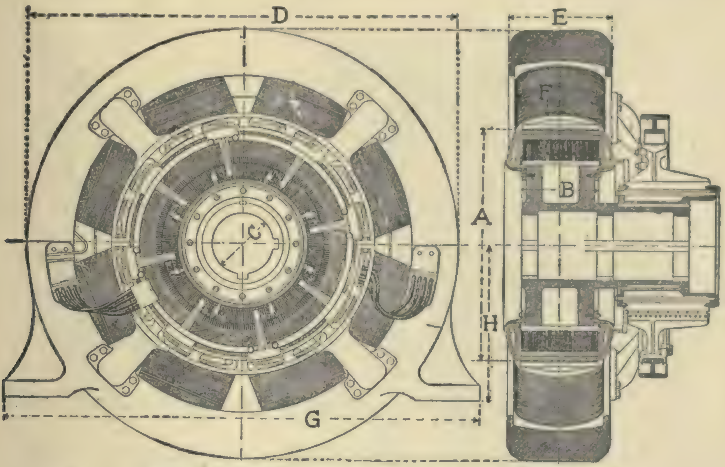

FIG. 11.—CROCKER-WHEELER MULTIPOLAR GENERATOR.

TABLE 9.

DIMENSIONS OF CROCKER-WHEELER MULTIPOLAR LOW, MEDIUM, AND HIGH SPEED SURFACE-WOUND RING-ARMATURE DYNAMOS. (See Fig. 11.)

Low Speed.		Medium Speed.		High Speed.		Nbr. of Poles.	Armature.				Field Frame.				
K. W	R. p. m.	K. W.	R. p. m.	K. W	R. p. m		A	B	C	Nbr. of Slots.	D	E	F	G	H
		2.5	1200	3.5	1600	4	7 3/16	3⅛	1⅛	40	17⅝	7½	2⅞	17⅝	6¾
		4.5	1150	5.75	1400	4	8½	3¼	1¼	44	19⅝	8	3 3/16	19⅝	7¾
		6.5	1050	8.25	1300	4	9½		1⅜	44	21⅝	8½	3 9/16	21⅝	8¾
		9	950	11.5	1300	4	11	5	1¾	87	25⅛	9¾	4⅛	25⅛	9¾
		13	900	17.5	1300	4	11⅝	6⅜	2	73	28	11¼	4 3/16	28	10¾
2	500					6	12	3½	1¾	62	21½	6¾	3½	21½	8½
		18	875	23	1150	4	13	7	2	99	30⅛	12⅛	4	30⅛	11¼
		22.5	850	27	1125	4	14	7½	2¼	78	32¼	13½	4 5/16	32¼	12¼
4	425					6	15	3⅜	2	50	25¼	6¾	3½	25¼	9½
		30	775	40	1050	4	15	8	2¾	95	36	14½	5 3/16	36	13¼
		45	700	55	930	4	16⅛	9	3	70	40⅛	15⅛	6¼	40⅛	15
7	400					8	19	4½	3	89	30½	8	3⅜	32	12
		65	625	80	750	4	19	10½	3⅛	96	48⅛	16¼	7¼	48⅛	18
9	350					8	21	5	3	73	33¼	8½	3⅞	33¼	13
15	325					8	22⅛	6½	3¼	65	36	11	7¾	40⅛	14⅜
20	300					6	20½	6¾	3⅛	76	39¼	13⅛	5 3/16	39¼	15
30	300					6	22½	8½	4	109	44½	13⅜	5⅛	44½	16
50	275	90	560	110	720	6	24	9⅜	4½	141	48½	15⅞	6¼	48½	18
60	275					6	28	11	4⅛	126	54⅛	17½	6⅛	54⅛	20
75	250	130	500	150	550	6	32⅛	12½	6	111	64¼	18	7⅞	68	24
		200	450			6	32½	13⅛	8	105	68¼	18⅜	9 3/16	68½	25
100	250					8	37	10⅞	6½	156	67	17	7¾	68	24
125	250					8	45	13	7	208	76⅜	18	7⅞	80	26
150	130	200	175	250	225	8	50	16¼	12	108	90	20¾	10⅝	99	29½
200	100	250	125	300	150	8	57	19	15	168	107	25¼	14	128	32
		300	100			12	77	14⅛		198	118½	24	12		
350	88	400	100	500	125	12	87	15⅜		160	135	25¼	13⅝		
				6 0	100	12	95	17¼		152	151	28¼	15⅝		

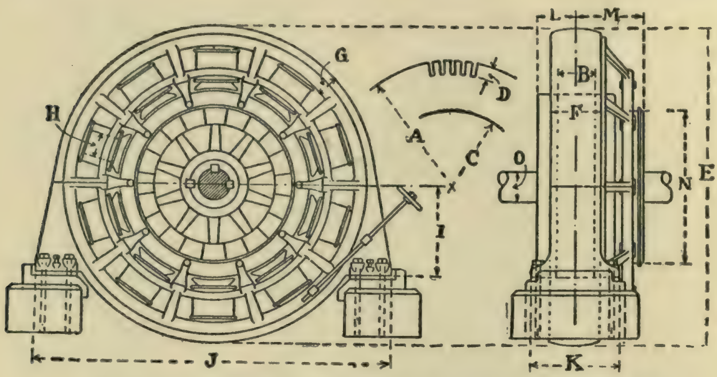

FIG. 12.—GENERAL ELECTRIC MULTIPOLAR GENERATOR.

TABLE 10.

DIMENSIONS OF GENERAL ELECTRIC MULTIPOLAR LOW-SPEED RING-ARMATURE GENERATORS.

(See Fig. 12.)

No.	K. W.	R. p. m.	No. of Poles.	Armature.					Approximate Weight.	
				A	B	C	D	No. of Slots.	Armature and Commutator.	Generator Complete.
1	150	200	6	46	$12\frac{5}{8}$	$26\frac{5}{16}$	$1\frac{5}{16}$	130	6400	29000
2	300	150	8	68	14	45	$1\frac{27}{32}$	272	17000	55000
3	400	120	8	72	$18\frac{1}{4}$	48	$1\frac{3}{4}$	240	22000	79000
4	500	120	10	84	$17\frac{1}{4}$	62	$1\frac{3}{4}$	280	25000	81000
5	800	80	14	120	$19\frac{1}{2}$	98	$1\frac{3}{4}$	364	50000	185000
6	1600	75	22	164	19	144	$1\frac{3}{4}$	440	74000	180000

No.	Magnet Frame.				General Dimensions.						
	E	F	G	H	I	J	K	L	M	N	O
1	99	25	$8\frac{11}{16}$	$13\frac{3}{4}$	23	114	35	$12\frac{7}{8}$	$19\frac{3}{4}$	32	9
2	125	27	10	$15\frac{1}{4}$	32	141	41	$16\frac{1}{8}$	$29\frac{3}{8}$	49	$11\frac{1}{2}$
3	135	$32\frac{1}{2}$	11	18	41	150	48	$18\frac{11}{16}$	$35\frac{7}{16}$	49	15
4	$144\frac{1}{2}$	30	$10\frac{3}{4}$	$16\frac{3}{4}$	44	154	45	$17\frac{3}{4}$	31	60	16
5	187	32	$11\frac{3}{4}$	18	53	201	48	$18\frac{5}{16}$	$34\frac{5}{16}$	84	19
6	230	24	$12\frac{5}{8}$	$16\frac{3}{4}$	63	245	48	$18\frac{3}{8}$	$37\frac{1}{2}$	120	24

TABLE 11.

RING-ARMATURE DIMENSIONS.

High Speed.				Medium Speed.				Low Speed.			
K. W.	R.p.m.	Diameter.	Length.	K. W.	R.p.m.	Diameter.	Length.	K. W.	R.p.m.	Diameter.	Length
				.1	1800	3	2				
				.15	1600	$3\frac{19}{32}$	$1\frac{5}{8}$				
				.25	1400	$4\frac{3}{4}$	$1\frac{7}{8}$				
				.5	1200	$5\frac{5}{8}$	$2\frac{1}{8}$				
				1	1000	7	$2\frac{3}{16}$				
				1.5	975	$7\frac{3}{4}$	$3\frac{5}{16}$				
				2.25	950	$8\frac{1}{4}$	$3\frac{9}{16}$	2	500	12	$3\frac{1}{4}$
				2.5	1200	$7\frac{3}{16}$	$3\frac{1}{8}$				
3.5	1600	$7\frac{3}{16}$	$3\frac{1}{8}$	4	925	$9\frac{3}{16}$	$4\frac{13}{16}$	4	425	15	$3\frac{3}{4}$
				4.5	1150	$8\frac{1}{2}$	$3\frac{1}{2}$				
5.75	1400	$8\frac{1}{2}$	$3\frac{1}{2}$	6.5	1050	$9\frac{1}{4}$					
				6.5	950	$9\frac{1}{4}$	6				
				6.5	875	$10\frac{1}{8}$	$5\frac{5}{8}$	7	400	19	$4\frac{1}{4}$
8.25	1300	$9\frac{1}{4}$		8.5	850	11	$6\frac{1}{4}$				
9	1450	$9\frac{1}{4}$	6	9	950	11	5	9	350	21	5
11.5	1300	11	5	13	900	$11\frac{5}{8}$	$6\frac{5}{8}$				
17.5	1300	$11\frac{5}{8}$	$6\frac{5}{8}$	13.5	850	13	$6\frac{1}{2}$	15	325	$22\frac{1}{2}$	$6\frac{1}{2}$
17.5	1175	13	$6\frac{1}{2}$	18	875	13	7				
23	1150	13	7	20	700	16	7	20	300	$20\frac{1}{4}$	$6\frac{3}{4}$
27	1125	14	$7\frac{1}{2}$	22.5	850	14	$7\frac{1}{2}$				
30	1050	16	7	30	775	15	8	30	300	$22\frac{1}{4}$	$8\frac{1}{4}$
40	1050	15	8	30	675	18	$8\frac{3}{4}$				
45	975	18	$8\frac{3}{4}$	45	700	$16\frac{1}{2}$	9	50	275	24	$9\frac{5}{8}$
55	930	$16\frac{1}{2}$	9	50	600	$20\frac{1}{4}$	$8\frac{3}{4}$	60	275	28	11
65	875	$20\frac{1}{4}$	$8\frac{3}{4}$	65	625	19	$10\frac{1}{2}$	75	250	$32\frac{1}{2}$	$12\frac{1}{4}$
80	750	19	$10\frac{1}{2}$	75	550	22	$9\frac{1}{4}$	100	250	37	$10\frac{7}{8}$
85	750	22	$9\frac{1}{4}$	90	560	24	$9\frac{5}{8}$	125	250	45	13
110	720	24	$9\frac{5}{8}$	130	500	$32\frac{1}{2}$	$12\frac{1}{2}$	150	200	46	$12\frac{5}{8}$
150	550	$32\frac{1}{2}$	$12\frac{1}{2}$					150	130	50	$16\frac{1}{2}$
200	450	$32\frac{1}{2}$	$13\frac{1}{2}$	200	375	50	$16\frac{1}{2}$	200	100	57	19
				250	225	50	$16\frac{1}{2}$	250	125	57	19
								300	150	57	19
								300	150	68	14
								300	100	77	$14\frac{1}{2}$
								350	88	87	$15\frac{3}{4}$
								400	120	72	$18\frac{1}{4}$
								400	100	87	$15\frac{3}{4}$
								500	125	87	$15\frac{3}{4}$
								500	120	84	$17\frac{1}{4}$
								600	100	95	$17\frac{3}{4}$
								800	80	120	$19\frac{1}{2}$
								1600	75	164	19

TABLE 12.

DRUM-ARMATURE DIMENSIONS.

High Speed.				Medium Speed.				Low Speed.			
K. W.	R. p. m.	Dia.	Length.	K. W.	R. p. m	Dia.	Length.	K. W.	R. p. m.	Dia.	Length.
.5	2400	$2\frac{5}{16}$	4					.56	1300	$5\frac{3}{4}$	$2\frac{5}{8}$
.75	2400	$2\frac{5}{8}$	5	.75	1900	$5\frac{3}{4}$	$2\frac{5}{8}$	1.5	1200	$6\frac{1}{2}$	$3\frac{1}{4}$
1.5	2100	$3\frac{25}{32}$	$6\frac{1}{2}$	1.875	1700	$6\frac{1}{2}$	$3\frac{1}{4}$	2.62	1050	$7\frac{3}{4}$	$4\frac{5}{8}$
3	1900	$4\frac{1}{2}$	8	3.75	1600	$7\frac{3}{4}$	$4\frac{3}{8}$	3.75	950	$8\frac{1}{2}$	$5\frac{1}{4}$
6	1800	$5\frac{11}{16}$	$9\frac{1}{4}$	5.62	1350	$8\frac{1}{2}$	$5\frac{1}{4}$	5.62	850	$9\frac{1}{2}$	$5\frac{1}{2}$
8.5	1700	$5\frac{7}{8}$	10	7.5	1250	$9\frac{1}{2}$	$5\frac{1}{2}$	7.5	750	$10\frac{1}{2}$	6
12	1600	$6\frac{1}{4}$	12	11.25	1150	$10\frac{1}{2}$	6	11.25	650	$11\frac{5}{8}$	$6\frac{3}{4}$
15	1500	$6\frac{3}{4}$	$13\frac{1}{2}$	15	1050	$11\frac{5}{8}$	$6\frac{3}{4}$	15	600	13	8
20	1400	$7\frac{3}{4}$	15	22.5	975	13	8	22.5	575	15	$8\frac{1}{2}$
25	1300	$8\frac{3}{4}$	$16\frac{1}{2}$	30	950	$13\frac{7}{8}$	$8\frac{1}{2}$	30	550	$15\frac{3}{4}$	$8\frac{1}{2}$
30	1200	$9\frac{3}{16}$	18	37.5	900	15	$8\frac{1}{2}$	37.5	550	$16\frac{1}{2}$	9
45	1000	$11\frac{1}{16}$	$20\frac{1}{2}$	45	850	$15\frac{3}{4}$	$8\frac{1}{2}$				
56.25	800	$16\frac{1}{8}$	9								
60	700	$12\frac{7}{8}$	$24\frac{1}{2}$								
100	650	$16\frac{3}{8}$	25								
150	450	$23\frac{3}{4}$	$26\frac{1}{2}$								
200	450	$23\frac{3}{4}$	$34\frac{1}{4}$								

It will be noted in Tables **11** and **12**, where machines of different manufacturers are placed side by side, that the armature dimensions of dynamos for similar output and speed in some instances vary greatly from one another, which goes to show that a wide range is given to the judgment of the designer in assuming the variable quantities such as peripheral speed, shape-ratios, etc. For instance, in Table **11** two *300 K. W. 150 revolution* armatures are given, the first having a diameter of 57 inches and a length of 19 inches, while the second has a diameter of 68 inches and a length of 14 inches. The peripheral velocity in the first machine is $v = \frac{57 \times \pi}{12} \times 150 = 2240$ feet p. min., while in the second it is $\frac{68 \times \pi}{12} \times 150 = 2670$ feet p. min. The length is $\frac{19}{57}$, or $\frac{1}{3}$ of the diameter in the first armature, and $\frac{14}{68}$, or about $\frac{1}{5}$ of the diameter in the second armature.

20. Specific Cross-Section of Armature Conductors.—It is customary to allow from 300 to 1,000 circular mils per ampere in armature conductors. The lower value applies to elevator motors and other machines that are used only intermittently, and seldom at full load, while the higher limit is for large machines running heavily loaded for long periods of time. An ordinary figure is 600 circular mils per ampere, which corresponds to a current density of about 2,000 amperes per square inch of cross-section.

One should be especially careful to determine correctly what fraction of the total current each conductor will have to carry, as follows:

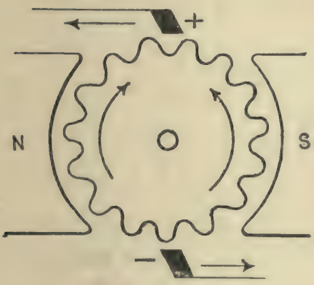

FIG. 13.—FLOW OF CURRENT IN BIPOLAR ARMATURE.

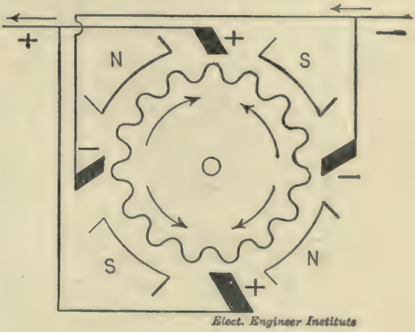

FIG. 14.—FLOW OF CURRENT IN MULTIPOLAR ARMATURE.

1. In a *bipolar* machine there are *two* paths through the armature winding (Fig. 13), so that one-half of the total current flows through any given inductor.
2. In a *multipolar* machine with the + and − brushes respectively connected in parallel (Fig. 14), or with cross-connected armature winding or commutator (Fig. 15, page 27), there are as many paths as there are poles, consequently the current in any conductor is the total amount divided by the number of poles.
3. In a *multipolar* machine the armature is sometimes

wound so that there are only two paths through it, being called a *two-circuit* winding (Fig. 16, page 27).

4. In *bipolar* or *multipolar* machines *two or more conductors* are often used in *parallel* to avoid the trouble of handling large wires, or in order to fit them into a certain space.

TABLE 13.

DATA OF BARE AND DOUBLE COTTON-COVERED WIRE

1	2	3	4	5	6	7	8	9
Size. B. & S.	Diam., inches, Bare Wire.	Area, Circular Mils. Bare Wire.	Lbs. per foot, Bare Wire.	Ohms per ft. at 20° C.	Max. Diam. of D. C. C. Wire.	Number of wires per inch. D. C. C.	Number of wires per square inch. D. C. C.	Resistance per cubic inch at 20° C. D. C. C.
5	.1819	33,124.	.1002	.000313	.197	5.1	25.8	.000673
6	.1620	26,244.	.0795	.000394	.177	5.6	31.9	.0010 0
7	.1443	20,736.	.0630	.000497	.159	6.3	39.6	.001638
8	.1285	16,384.	.0500	.000627	.143	7.0	48.9	.00256
9	.1144	12,996.	.0396	.000791	.129	7.8	60.2	.00396
10	.1019	10,404.	.0314	.000992	.117	8.5	78.1	.00607
11	.09074	8,281.	.0249	.00126	.106	9.4	89.0	.00934
12	.08081	6,561.	.0198	.00159	.093	10.8	115.6	.01526
13	.07196	5,184.	.0157	.00200	.084	12.0	145.2	.02410
14	.06408	4,096.	.0124	.00252	.075	13.3	177.8	.0373
15	.05707	3,249.	.0099	.00318	.067	14.9	222.8	.0590
16	.05082	2,601.	.0078	.00401	.061	16.4	268.7	.0896
17	.04526	2,025.	.0062	.00506	.055	18.2	330.6	.1392
18	.04030	1,600.	.0049	.00638	.050	20.0	400.0	.2124
19	.03589	1,296	.0039	.00804	.046	21.7	473.5	.3172
20	.03196	1,024.	.0031	.01014	.042	23.8	566.9	.4790
21	.02846	812.3	.00245	.01275	.038	26.3	692.5	.7375
22	.02536	640.1	.00195	.01608	.035	28.6	876.3	1.0963
23	.02257	510.8	.00154	.02030	.033	30.3	918.3	1.555
24	.02010	404.	.00122	.02560	.030	33.3	1111.1	2.373
25	.01790	320.4	.00097	.03225	.028	35.7	1276.4	3.436
26	.01594	252.8	.00077	.04075	.026	38.5	1479.3	5.022

21. Data for Armature Winding.—The data given in the above Table **13** will be found useful by the student when calculating an armature. The table gives the area, diameter, specific weight, specific resistance, the number of wires that can be wound in a given space, and the resistance per cubic inch of winding for the sizes usually employed for generator and motor armatures. Columns *6* to *9* refer to Double Cotton-Covered (D. C. C.) wire, this being the kind of insulation usually employed on conductors for armature winding. Wires larger than No. 5 B. & S. are commonly not used, on account of the greater difficulty of handling and winding; if a larger area than 33,000 circular mils is required, two wires of one-half, or three wires of one-third the requisite cross-section, etc., are used.

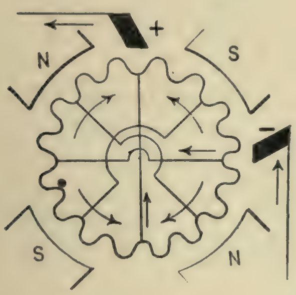

Fig. 15.—Flow of Current in Cross Connected Multi-polar Armature.

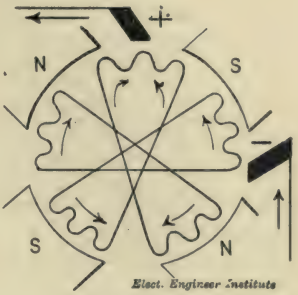

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Fig. 16.—Flow of Current in Multipolar Two-Circuit Winding.

22. Examples showing Use of Winding Table.—The use of the various data given in Table **13** is seen from the following example. Suppose an *18×25* inch smooth drum armature is wound to a height of about .6 inch with No. *5* B. & S. wire, this size being determined, as shown in Pars. **23** to **25**, by finding the requisite cross-section for the current to be carried and comparing the result with the figures given in the third column of Table **13**.

The periphery of the armature is $18 \times \pi = 56.55$ inches; hence, by column 7, the number of wires per layer, when allowing 8 per cent. of the armature circumference for division strips and spaces, is $56.55 \times .92 \times 5.1 = 265$. The number of layers is $.6 \times 5.1 = 3$; hence there are, in all, $265 \times 3 =$ *795* wires on the armature.

The latter result can also be obtained approximately from column *8*, thus: 56.55 × .92 × .6 × 25.8 = *805* wires, which is a few per cent. in excess of the actual value, owing to the use of .6 instead of 3 × .197 = .591 as the height of the winding space.

The length of one complete turn on this armature is about 9 feet, and includes 2 wires; consequently the weight of wire, by column *4*, is $\frac{795}{2} \times 9 \times .1002 = 358$ lbs., and its total resistance, all in series, at 20° C., by column *5*, is $\frac{795}{2} \times 9 \times .000313 = 1.12$ ohm.

The resistance can also be obtained in the following manner: The cubical contents of the winding space is 56.55 × .591 × 25 = 835 cubic inches. Doubling this figure, to allow for the heads and commutator connections, we have, from column *9*: 835 × 2 × .000673 = *1.124* ohm as the approximate total resistance R_a of the wire on the armature (see Par. **39**).

23. Approximate Size of Armature Conductors.—It follows from Par. **20** that the approximate cross-section of the armature conductor for a given case is found by multiplying the current flowing through it by the specific cross-section suited for that case. Having in this manner found the number of circular mils of area required, the size of the wire is taken from column *3*, Table **13**.

24. Example of Bipolar Armature.—*What size of conductor will be required on the armature of a* **5 H. P.** *bipolar motor for* **110**-*volt circuit?*

Solution.—5 H. P. is equivalent to 5 × 746 = 3.730 watts output. Assuming 85% efficiency as a fair value for this size, the watts input are 3,730 ÷ 85 = 4,388 watts. The current is 4,388 ÷ 110 = 40 amperes, hence each conductor must carry one-half of 40, or 20 amperes, which at 600 circular mils per ampere requires a wire of 12,000 cir. mils. Referring to Table **13**, the nearest size is found to be No. **9** B. & S., having a cross-section of 12,996 cir. mils.

25. Example of Multipolar Armature.—*Find the approximate size of armature conductor for a* **200-K. W., 6**-*pole,* **550**-*volt railway generator.*

Solution.—The total current will be 200 × 1,000 ÷ 550 = 364 amperes, which will be divided between six paths if the armature is cross-connected, each conductor carrying 364 ÷ 6 = 61 amperes, and requiring a cross section of 61 × 600 = *36,600* C. M. The nearest larger size of wire is *No. 4* with 41,616 C. M. If it be desired to subdivide this in order to facilitate winding or placing in a certain size of slot, it is possible to substitute *two No. 7* wires in parallel, having a combined cross-section of 41,472 C. M. For a two-circuit winding, each conductor would have to carry one-half the total current, or 182 amperes, requiring a cross-section of 182 × 600 = *109,200* C. M., which is somewhat larger than a *No. 0* wire (105,625 C. M.) This would be still more clumsy to handle, and might be replaced by *two No. 3* or by *four No. 6* wires in parallel.

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THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS.

FINAL CALCULATION OF ARMATURE.

26. Number of Inductors on Armature.—The size of the inductors having been ascertained, the designer may proceed to determine the number of them that can be properly placed upon the armature core, the approximate size of which has been computed. The number of inductors that can be placed upon the circumference of a smooth core, or into the slots of a toothed armature, depends upon the height to which it is expedient to wind the armature, this height, in a toothed core, corresponding to the depth of the slots. The height of the armature winding, h_a (Figs. 17 and 18, page 45), varies with the type and size of the armature, and can be taken approximately from Table **14**, which gives average values for various cases.

The total winding space, S_w, of a *smooth-core armature* is roughly given by the following formula, provided that h_a is very small compared with D_a, which is practically always the case:

$$S_w = D_a \pi \times h_a \text{.................... } \mathbf{(14)}$$

In ordinary smooth-core machines, from $\frac{2}{5}$ to $\frac{1}{2}$ of this total winding space is occupied by insulation, division strips, binding bands, etc., hence the available inductor space is:

$$S_w' = .55 S_w = .55 D_a \pi \times h_a = 1.75 \times D_a \times h_a \text{.... } \mathbf{(15)}$$

The number of inductors on the armature is the inductor space, S_w', divided by the space occupied by one inductor. Calling the diameter of the bare inductor d_a, each inductor takes up the space d_a^2. The approximate total number of inductors, N, on a smooth-core armature can therefore be obtained from :

$$N = \frac{S_w'}{d_a^2} = 1.75 \times \frac{D_a \times h_a}{d_a^2} \ldots\ldots\ldots\ldots \quad \textbf{(16)}$$

In *toothed armatures,* the slots usually take up about one-half of the circumference, and only about three-fifths, or .6, of the total slot area is actually occupied by the inductors, approximately one-fifth of the slot area being used up by the slot lining and about one fifth of it by the wire insulation. Hence, the approximate total number of inductors is :

$$N = \frac{.5 \times .6 S_w}{d_a^2} = \frac{.3 \times D_a \pi \times h_a}{d_a^2} = \frac{D_a \times h_a}{d_a^2} \ldots \quad \textbf{(17)}$$

The figures obtained by **(16)** and **(17)** should be checked by means of Table **13,** as shown in Par. **22.**

TABLE 14.

AVERAGE HEIGHT OF WINDING SPACE ON ARMATURES.

Diameter of Armature, in Inches. D_a.	Approximate Height of Winding Space, h_a.		
	Smooth Armature Core.		Toothed Armature.
	Drum.	Ring.	
2″	$\frac{1}{4}$″	..	..
4	$\frac{5}{16}$	$\frac{7}{32}$″	..
6	$\frac{3}{8}$	$\frac{1}{4}$	$\frac{5}{8}$″
10	$\frac{1}{2}$	$\frac{9}{32}$	$\frac{3}{4}$
15	$\frac{5}{8}$	$\frac{5}{16}$	1
20	$\frac{3}{4}$	$\frac{3}{8}$	$1\frac{1}{4}$
30	$\frac{7}{8}$	$\frac{7}{16}$	$1\frac{1}{2}$
50	..	$\frac{1}{2}$	$1\frac{3}{4}$
75	..	$\frac{5}{8}$	2
100	..	$\frac{3}{4}$	$2\frac{1}{2}$
150	..	$\frac{7}{8}$	$3\frac{1}{4}$
200	..	1	4

27. Arrangement of Inductors on Smooth-Core Armature.—The number of inductors found by formula (**16**) must be modified according to the number of divisions and to the manner of winding of the armature. The number of divisions of a smooth-core armature is either equal to, or twice, the number of commutator segments, the latter depending upon the voltage and on the number of poles of the machine. For machines up to *300* volts, the commutator is usually divided into from *40* to *60* segments per pair of poles. For higher potentials, a correspondingly greater number of segments is provided; thus, for *500* volts up to *100* segments, and for *1,000* volts up to *150* segments, per pair of poles are used.

In a smooth armature, the number of wires per layer must be a whole multiple of the number of armature divisions; to find the final number of wires per layer, therefore, multiply the circumference of the armature (diminished by the space allowed for division strips) by the number of wires per inch (column 7, Table **13**); divide the result by the number of commutator segments, and note the quotient so obtained. If this quotient is not quite a whole number, but so nearly so, that the deficiency can be made up by a moderate reduction of the allowance made for division strips, the number per layer is the product of the raised quotient by the number of commutator segments. If the quotient is but little greater than a whole number, the number of wires per layer is the next smaller whole number multiplied by the number of commutator segments. If the quotient is not sufficiently near a whole number to allow one or the other of the above methods to be employed, either the next smaller or the next larger whole number must be taken and the number of commutator segments so adjusted that the product of the two numbers is equal to, or slightly less than, the number of wires previously obtained by multiplying the available circumference by the number of wires per inch.

The corrected number of wires per layer is then multiplied by the number of layers, which, in turn, is found by multiplying the height of the winding space by the number of wires per inch and rounding the result to the next smaller whole number.

In case of but a few layers of heavy wire, if the calculated number of layers is a considerable fraction above a whole number, it is even advisable to replace the armature conductor by two or more wires of equivalent total cross-section, and to re-design the arrangement of the armature winding so that the permissible winding space is made use of more economically.

The actual total number of inductors on the armature is then the number of armature divisions times the number of wires per division, divided by the number of wires employed in subdividing the area of the armature conductor.

28. Arrangement of Wires on Toothed Armature.

—The number of slots of a toothed armature is governed by its size, the usual limits of the slot numbers for various sizes of toothed armatures being given in Table **15**, for reference.

TABLE 15.

NUMBER OF SLOTS IN TOOTHED ARMATURES.

Diameter of Armature.	Number of Slots.
5 inches.	25 to 40
10 "	30 " 60
15 "	40 " 80
20 "	60 " 100
30 "	80 " 150
50 "	100 " 200
100 "	150 " 300
150 "	200 " 400

Dividing the total number of wires, obtained from formula (**17**), by the number of slots, taken from Table **15**, the number of wires per slot is obtained. The latter must be such that the slot is evenly filled with the winding; that is to say, the slot must contain a proper number of full layers nearly filling the space within the slot lining. If this condition is not obtained by the first selection of the slot number, a second, and eventually a third, must be chosen within the given limits, and, if necessary, even the size of conductor must be changed by suitable subdivision of the cross-section.

It usually happens, in case of smooth as well as of toothed armatures, that a particular size of wire will not suit a certain case, and it is often very difficult to find any regular size that will fit exactly right. In fact, it is a large part of the work of designing a machine to make these relations come out satisfactorily. If necessary, a special size of wire can be made to order, but this should be done only as a last resort.

29. Example of Smooth-Core Armature.—*How many No.* **6** *B. & S. wires can be wound upon a smooth-core drum armature* **10** *inches in diameter?*

Solution.—Here $D_a = 10''$; $d_a = .162''$, $d_a^2 = .026244$ (compare with column *3* of Table **13**); and from Table **14** we find that the average winding depth for this size of armature is about *.5* inch; hence, by formula (**16**):

$$N = \frac{1.75 \times 10 \times .5}{.026244} = \mathbf{332} \text{ wires.}$$

In order to verify this result, we find in Table **13** that the diameter of No. *6* B. & S. wire, including its double cotton covering, which is almost always used for armature winding, is *.177* inch. The circumference of the armature is $10 \times \pi = 31.416$ inches, *90* per cent. of which, or *28.27* inches, is occupied by the winding; hence, the number of wires per layer is $28.27 \div .177 = 160$.

The core insulation and binding in an armature of the size under consideration will amount to a height of about ⅛ inch; hence, the number of layers that can be placed on this armature is $\frac{.5 - \frac{1}{8}}{.177} = 2$, and the total number of inductors, therefore, $160 \times 2 = 320$, which agrees very well with the result obtained by formula (**16**).

Assuming that a commutator of *54* divisions is to be used with this armature, the number of conductors must be modified as follows: Number of wires per layer of armature section is 160 ÷ 54 = 2.96; taking *3* wires, we have *54* × *3* = *162* wires per layer; and since there are *2* layers, the actual number of wires on this armature will be *162* × *2* = **324,** or 2 × 3 = 6 wires per commutator division.

30. Example of Toothed Armature.—*Find the approximate number of No.* **9** *B. & S. wires that can be placed on a toothed armature having a diameter of* **18** *inches.*

In this case $D_a = 18''$, $h_a = 1.15$ (by interpolation from Table **14**), and $d_a^2 = .013$, nearly, (from Table **13**); therefore, by formula (**17**):

$$N = \frac{18 \times 1.15}{.013} = \mathbf{1590} \text{ wires.}$$

This result may be checked as follows: The circumference of the armature under consideration is *18* × π = *56.55* ins., about one-half of which, or *28.3* ins., is occupied by the slots. The slots being *1.15* inch deep, the total slot area is *28.3* × *1.15* = *32.5* square inches. Of this area, only about four-fifths is actually occupied by the conductor, including its own cotton covering; hence, the effective slot area is *32.5* × $\frac{4}{5}$ = *26* square inches.

According to Table **13**, the number of No. *9* wires, D. C. C., which can be wound in one square inch is *60.23*; consequently we have *26* × *60.23* = **1566** as the total number of conductors, which agrees with the above result obtained by formula (**17**).

According to Table **15,** the average number of slots for an armature of the size considered is about *80*; hence, the number of wires per slot is *1590* ÷ *80* = *20*. The width of the slot is the available circumference divided by the slot number, or *28 3* ÷ *80* = *.35* inch, while its depth, h_a, is *1.15*. Deducting $\frac{1}{32}$ inch for lining of the sides and the bottom of the slot, the available depth of the slot becomes $1.15 - .031 = 1.119$ inch, and the available width $.35 - (2 \times .031) = .288$ inch.

The diameter of No. 9 D. C. C. wire is .129 inch; the depth of the slot will therefore take $1.119 \div .129 = 9$ wires, and the width will take $.288 \div .129 = 2$ wires, giving a total of 18 wires per slot. In order to accommodate 9 wires in height, the depth of the slot must be slightly increased, the size required being $(9 \times .129) + .031 = 1.2$ inch. On the other hand, the width of the slot is not completely filled by the 2 wires, hence a more economical arrangement will be obtained by using a correspondingly greater number of narrower slots.

The width required for 2 wires and 2 slot insulations is $2 \times (.129 + .031) = .32$; hence, we may have $\frac{(.35 - .32) \times 80}{.32} = 7.5$ additional slots. Taking 8, the nearest even whole number, the corrected number of slots is $80 + 8 = 88$, and the total number of wires that can actually be placed on the armature is $88 \times 18 =$ **1584.**

31. Approximate Length of Active Armature Inductor.

Approximate Length of Active Armature Inductor.—The length of armature inductor required to generate a given E. M. F. can be computed from the fundamental fact that 1 volt E. M. F. in a generator, or counter E. M. F. in a motor, is generated when lines of force are cut at the rate of 100,000,000, or 10^8, lines per second.

Accordingly, each foot of inductor, when moving at the rate of 1 foot per minute in a magnetic field having a density of 1 line per square inch, since it moves across 1 square foot (= 144 square inches) of field, and therefore cuts 144 lines of force per minute, or $144 \div 60 = 2.4$ lines per second, generates

$$\frac{2.4}{100,000,000}, \text{ or } 2.4 \times 10^{-8} \text{ volt.}$$

If there are l_a feet of inductor on the armature, the voltage

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generated is l_a times as great as that produced by *1* foot of inductor. If the armature revolves with a velocity of v feet per minute, the voltage generated is v times as great as when moving at the rate of *1* foot per minute. If the magnetic density in the air gaps is $\mathbf{B}_g$ lines per square inch, the voltage is $\mathbf{B}_g$ times that for a field density of *1* line per square inch. On account of the fact that the polepieces do not completely surround the armature, not all of the inductors are cutting lines at the same time. The number of *idle* inductors usually varies from *15* to *25* per cent., and averages about *17* per cent.; hence, the *effective* length of the inductors is 100 − 17 = *83* per cent., or *.83* of the total length of inductors. If the armature winding consists of n_p pairs of parallel branches, the voltage generated by the $.83 l_a$ feet of useful inductors must be divided by $2n_p$, since the total voltage is generated in each of the $2n_p$ branch circuits. The total E. M. F. generated in an armature is therefore given by the formula:

$$E = 2.4 \times 10^{-8} \times \frac{.83 \times l_a \times v \times \mathbf{B}_g}{2n_p} = \frac{l_a \times v \times \mathbf{B}_g \times 10^{-8}}{n_p}, \quad .. \; \mathbf{(18)}$$

from which the length of the armature inductor required to generate the voltage E is found, in feet:

$$l_a = \frac{E \times n_p \times 10^8}{v \times \mathbf{B}_g} \quad \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(19)}$$

The E. M. F., E and the number of *bifurcations*, or pairs of armature circuits, n_p, being given, the fitness of the result depends upon the correct assumption of the velocity, v, and of the field density, $\mathbf{B}_g$. The former has already been discussed in Par. **14**, the latter is treated in Par. **32**.

32. Field Density.—The density of the magnetic field, or the *gap induction*, as it is sometimes called, must be properly chosen according to the size of the machine, the number of poles, the form of the armature, and the material of the polepieces. In general, the density is taken the higher, the larger the output of the machine, and the greater the number of poles. In dynamos with smooth-core armatures, the densities are made greater than in those with toothed cores; and in a machine having wrought iron or steel polepieces, the density can be chosen about *50* per cent. higher than in a similar machine with cast iron poles.

Suitable average values of $\mathbf{B}_g$ for ordinary dynamos and motors are given in Table **16.**

TABLE 16.

AVERAGE FIELD DENSITIES FOR DYNAMOS AND MOTORS, IN LINES PER SQUARE INCH.

Capacity in K. W.	Bipolar Dynamos.				Multipolar Dynamos.			
	Smooth Armature.		Toothed Armature.		Smooth Armature.		Toothed Armature.	
	Cast Iron Pole-pieces.	Steel Pole-pieces.	Cast Iron Pole-pieces.	Steel Pole-pieces.	Cast Iron Pole-pieces.	Steel Pole-pieces.	Cast Iron Pole-pieces.	Steel Pole-pieces
.1	10000	15000	8000	12000	14000	20000	12000	18000
.25	12000	18000	10000	15000	16000	24000	14000	21000
.5	14000	20000	12000	18000	18000	27000	16000	24000
1	15000	22000	13000	19000	19000	28000	17000	25000
2.5	16000	24000	14000	20000	20000	29000	18000	26000
5	17000	25000	15000	22000	21000	30000	19000	28000
7.5	18000	26000	16000	24000	22000	32000	20000	30000
10	19000	28000	17000	25000	24000	35000	21000	32000
25	20000	30000	18000	27000	26000	38000	22000	35000
50	22000	33000	20000	30000	28000	41000	23000	38000
100	24000	36000	22000	33000	30000	44000	25000	40000
200	27000	40000	24000	36000	32000	47000	27000	42000
300	30000	45000	27000	40000	35000	50000	29000	44000
500	....	....	....	....	38000	53000	31000	46000
1000	....	....	....	....	41000	56000	33000	48000
2000	....	....	....	...	45000	60000	35000	50000

If a strong magnetic field is desired for the purpose of preventing, or diminishing, the distorting effect of armature reaction, values of the gap induction about *20* to *30* per cent. in excess of those given in the above table are usually taken.

For machines having a very low voltage, such as *electroplating machines, battery motors,* etc., or for generators in which the amperage is relatively very high, as in *incandescent generators of large outputs,* the field density is usually taken about two-thirds or three-fourths of the density employed under similar conditions for ordinary machines.

33. Length of Armature Core.—Having computed the required length of active wire, l_a, from (**19**), while the number of inductors, N, has been found in accordance with Pars. **26** to **30,** the length of the armature core, L_a, in inches, may be obtained by dividing the length of active wire, expressed in inches, by the number N, or in symbols:

$$L_a = \frac{12\, l_a}{N} \dots\dots\dots\dots\dots\dots \textbf{(20)}$$

The above method of obtaining the length of the armature by finding the length of active wire, necessitates the assumption of the field density. Another plan is to compute the total flux from the number of inductors, as will be shown in Par. **34,** and to adjust the length of the armature so that the final density attains a proper value. The latter method is simpler, because it is independent of exact dimensions and involves only total values.

34. Preliminary Determination of Flux in Armature.—With a given number of inductors, N, the total flux, Φ, passing through the armature must be such as to give E, the E. M. F. generated, at the specified number of revolutions per minute, n_1. Remembering that the lines of flux are cut twice per revolution by each inductor, and that the number of inductors in series to generate E volts is $\frac{N}{2n_p}$, when n_p denotes the number of pairs of parallel branches in the armature, we have:

$$E = 2\Phi \times \frac{N}{2n_{\text{p}}} \times \frac{n_1}{60} \times 10^{-8} \text{ volts,}$$

from which $\Phi = \dfrac{60 \times 10^8 \times 2n_{\text{p}} \times E}{2 \times N \times n_1} = \dfrac{6 \times 10^9 \times n_{\text{p}} \times E}{N \times n_1} \ldots$(**21**)

The value of Φ can also be found when the flux density, $\mathbf{B}_{\text{g}}$, in the air gap, the length, L_{a}, of the armature, and its diameter, D_{a}, are known. If in this case the average percentage of the idle inductors is taken as *17*, see Par. **31,** the flux in the armature is obtained as follows:

$\Phi = \frac{1}{2}\mathbf{B}_{\text{g}} \times .83 D_{\text{a}}\, \pi \times L_{\text{a}} = 1.3 \times \mathbf{B}_{\text{g}} \times D_{\text{a}} \times L_{\text{a}} \ldots$(**22**)

If $\mathbf{B}_{\text{g}}$ is not given, it may be assumed from Table **16.** As stated in Par. **33,** however, this indirect method is not as satisfactory as the direct method represented in (**21**), but it may be used as a check on the latter.

Equations (**21**) and (**22**) apply to multipolar as well as to bipolar machines. In case of *bipolar* dynamos the total flux, Φ, in the armature is the number of lines which enter it from the polepiece of North polarity, while in a *multipolar* field it is the *sum* of the lines that enter it from *all* of the North poles. The same lines pass out through the South pole-faces; hence, Φ is one-half of all the lines entering and leaving the armature. For this reason, the factor *2* is used in (**21**), and the factor $\frac{1}{2}$ in (**22**). The student should be careful to avoid confusion on this point, especially as the flux per pole and the flux per magnetic circuit are often used in calculations, instead of the total flux.

Before the flux Φ is computed by (**21**) or (**22**), the approximate size of the armature should be determined by the methods given in Pars. **13** to **18,** otherwise the resulting flux density in the armature core might either be absurdly high, that is, above the practical magnetic saturation point, or else far below the normal value. It must be borne in mind that all of these preliminary calculations are tentative, the object being to reconcile and adjust the various elements, so that in the end a harmonious result will be obtained.

35. Example.—*The armature of a bipolar ring dynamo is required to generate* **10** *kilowatts at* **120** *volts when running at* **350** *revolutions per minute, the total number of armature inductors being* **400.** *What should be the total flux through the armature?*

Solution.—In bipolar dynamos, according to Par. **20**, there are *2* paths for the current in the armature; hence, n_p, the number of pairs of parallel branches, is *1*, and we have from (**21**):

$$\Phi = \frac{6 \times 10^9 \times 120}{400 \times 350} = \mathbf{5,140,000} \text{ lines of force.}$$

By (**6**) the given armature has a diameter of about

$$D_a = 3.8 \times \frac{2000}{350} = 21.7 \text{ inches.}$$

Inserting this value into formula (**13**), we have

$$21.7 = \sqrt{\frac{s \times k \times W}{2\pi \times (1 - m') \times (m + m')}}.$$

In the present case $W = 10{,}000$ watts. Taking $s = 1$ (Par. **16**), $k = .12$ (Table **3**), and assuming $m' = .10$ (Table **4**), the above equation becomes:

$$21.7^2 = \frac{1 \times .12 \times 10\,000}{6.28 \times (1 - .10) \times (m + .10)}$$

$$= \frac{1200}{(6.28 \times .90 \times m) + (6.28 \times .90 \times .10)};$$

from which follows:

$$m = \frac{1200 - (21.7^2 \times 6.28 \times .90 \times .10)}{21.7^2 \times 6.28 \times .90} = \frac{934}{2660} = .35.$$

The approximate length of the armature is, therefore:

$$L_a = .35 \times 21.7 = 7.6 \text{ inches.}$$

From Table **16**, the proper value of the field density, for cast steel poles, is found to be $\mathbf{B}_g = 28{,}000$ lines per sq. in.; hence by (**22**):

$$\Phi = 1.3 \times 28{,}000 \times 21.7 \times 7.6 = \mathbf{6,000,000} \text{ lines of force,}$$

which shows that the result obtained by (**18**) is practical.

36. Radial Depth of Armature Core.—The cross-section of the armature core must be made of sufficient area to carry the flux Φ given by (**21**) without over saturation of the iron and without causing excessive power losses due to hysteresis and eddy currents. The length, L_a, of the core having been determined by (**20**), the radial thickness of the armature core, B_a, is obtained thus:

$$B_a = \frac{\Phi}{2n_p \times L_a \times \mathbf{B}_a}, \dots\dots\dots\dots\dots (23)$$

where n_p is the number of pairs of magnet poles, and $\mathbf{B}_a$ the flux density in the armature. The latter should be chosen within the limits given in Table **17**.

TABLE 17.

FLUX DENSITIES IN ARMATURE CORE.

Kind of Machine.	Flux Density in Armature.
Ordinary Bipolar Dynamos and Motors..............	60,000 to 90,000 lines p. sq. in.
Ordinary Multipolar Dynamos and Motors..........	50,000 " 70,000 " " "
Arc Lighting Machines....	100,000 " 130,000 " " "
Dynamos for Plating, Accumulator-Charging, etc., and Battery Motors	30,000 " 50,000 " " "
Alternators	20,000 " 40,000 " " "

37. Example.—*Find the radial depth of a smooth-core ring armature of* **45** *inches diameter, having* **1,200** *inductors and generating* **550** *volts when revolving at a speed of* **200** *revolutions per minute in a* **6**-*pole field having a density of* **40,000** *lines per square inch.*

Solution.—From formula (**5**) we have

$$v = \frac{45 \times 200}{3.8} = 2{,}360 \text{ ft. p. min.};$$

therefore, by (**19**):

$$l_a = \frac{550 \times 3 \times 10^8}{2,360 \times 40,000} = 1,750 \text{ feet},$$

and by (**20**):

$$L_a = \frac{12 \times 1,750}{1,200} = 17.5 \text{ inches}.$$

The total flux is obtained from (**21**), thus:

$$\Phi = \frac{6 \times 10^9 \times 3 \times 550}{1,200 \times 200} \; 41,200,000 \text{ lines of force}.$$

Taking the average value of $\mathbf{B}_a$ for multipolar dynamos given in Table **17**, namely $\mathbf{B}_a = 60,000$, the required radial depth is found by formula (**23**):

$$B_a = \frac{41,200,000}{6 \times 17.5 \times 60,000} = \mathbf{6.5} \text{ inches}.$$

Subtracting twice this depth from the external diameter, the internal diameter of the given armature is found to be $45 - 13 = 32$ inches.

38. Total Length of Armature Conductor.—The active or inductive length, l_a, of the armature conductor being known by (**19**), the total length of wire on the armature may be obtained approximately by making due allowances for the inactive length required to join the active portions of the armature conductors into continuous turns, or convolutions.

In a *drum armature* the total length of wire, l_A, depends upon the ratio of diameter to length of armature core and is given approximately, in feet, by the formula:

$$l_A = l_a \times \left(1 + \frac{k \times D_a}{L_a}\right) \ldots\ldots\ldots\ldots (\mathbf{24})$$

Since the total active length is more accurately obtained by multiplying the number of conductors by the active length of one conductor, formula (**24**) can also be written in the form

$$l_A = N \times \frac{L_a}{12} \times \left(1 + \frac{k \times D_a}{L_a}\right) = \frac{N}{12}\left[L_a + (k \times D_a)\right], \ldots (\mathbf{25})$$

in which k is a constant varying between the following values, according to the diameter of the armature and to the height of the winding space, the average length of a convolution (Fig. 17) being the greater, the larger the area of the shaft and that of the winding space as compared with the end-surface of the armature core:

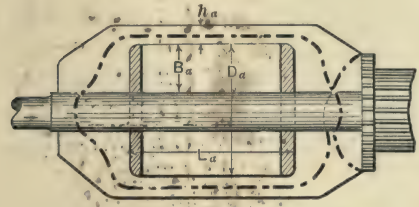


FIG. 17—CONVOLUTION ON DRUM ARMATURE.

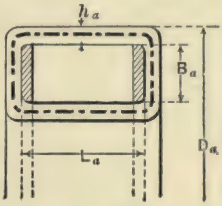


FIG. 18 – LENGTH OF MEAN TURN IN RING ARMATURE.

For *smooth-core drums*, k = *1.25* to *1.75;* average, k = **1.5;**
" *toothed drums*, k = *1.5* to *3.0;* average, k = **2.25.**

The smaller values apply to large armatures having a comparatively small winding depth (below the average given in Table **14**), whereas the larger values are for small armatures in which the winding depth is comparatively large (above the corresponding average given in Table **14**).

For a spirally wound *ring armature*—that is, one in which the turns are completed spirally by winding the inner surface of the ring—the total length of the armature wire is directly given by the dimensions of the armature core, thus:

$$l_A = N \times \frac{2L_a + 2B_a + h_a\pi}{12}, \ldots\ldots\ldots\ldots \textbf{(26)}$$

where l_A = total length of armature wire, in feet;
N = number of armature inductors;
and $(2L_a + 2B_a + h_a\pi)$ = length of mean turns, in inches (see Fig. 18), L_a being the length and B_a the radial thickness of the armature core, and h_a the winding depth.

In case of *formed coils*, which are separately completed by means of formers and placed upon the *exterior* surface of the armature, the total length of the winding is found from formula **(24)** or **(25)**, in which then the constant k has the following approximate values:

For coils spanning $\frac{1}{4}$ circumference (*4* poles), $k = 1.2$
" " " $\frac{1}{6}$ " (*6* "), " $= .8$
" " " $\frac{1}{8}$ " (*8* "), " $= .6$
" " " $\frac{1}{10}$ " (*10* "), " $= .5$
" " " $\frac{1}{12}$ " (*12* "), " $= .4$
" " " $\frac{1}{16}$ " (*16* "), " $= .3$
" " " $\frac{1}{24}$ " (*24* "), " $= .2$

39. Armature Resistance.—The electrical resistance of the armature winding is determined by the total length of wire wound on the armature and by the sectional area of the conductor. If R_a denotes the total resistance of the armature wire, all in one continuous length, and if there are n_p bifurcations in the armature, and, therefore, $2n_p$ electrically parallel armature circuits, then the armature forms the combination of $2n_p$ parallel branches of $\frac{R_a}{2n_p}$ ohms resistance each; their joint resistance, r_a, which is the actual armature resistance, will consequently be:

$$r_a = \frac{1}{2n_p} \times \frac{R_a}{2n_p} = \frac{R_a}{4n_p^2}.$$

The total resistance R_a of the armature conductor is the product of the total length l_A and the resistivity, ρ_f, in ohms per foot of the conductor, hence the armature resistance:

$$r_a = \frac{l_A \times \rho_f}{4n_p^2} \qquad\ldots\ldots\ldots\ldots\ldots\ldots\ldots(27)$$

In case that the armature conductor is subdivided into two or more wires, the resistivity of that wire must be divided by the number of wires used in parallel. The resistivities, ρ_f, of the various sizes of armature wire at 20° C. (68° Fahr.) are given in column *5* of Table **13**. When using these figures, therefore, the armature resistance found by (**27**) is that at ordinary room temperature, or is the *cold* resistance of the armature when the machine is not running. In order to obtain the *warm* armature resistance, add *1* per cent. for every *2½* degrees C. over 20° C., or *1* per cent. for every *4½* degrees Fahr. over 68° F. Thus, if the temperature of the armature, when running at full load, is about *60°* C. (= *140°* F.), which is the usual limit given in dynamo specifications, the value found by (**27**) must be increased by $\frac{60 - 20}{2\frac{1}{2}} = \frac{40}{2.5}$ $= 16$ per cent., or must be multiplied by **1.16**. Figuring in Fahr. degrees, we have $\frac{140 - 68}{4\frac{1}{2}} = \frac{72}{4.5} = 16$ per cent., the same as before.

40. Example of Drum Armature.—*A bipolar drum armature,* **16** *inches in diameter and* **25** *inches in length, contains* **192** *inductors, each consisting of* **3** *No.* **5** *B. & S. wires. What is the armature resistance at* **70°** *C.?*

Solution.—In this case $N = 192$, $L_a = 25$, $D_a = 16$, and $k = 1.5$ (the armature being of medium size); hence, by (**25**):

$$l_A = \frac{192}{12}(25 + 1.5 \times 16) = \frac{192 \times 49}{12} = 784 \text{ feet.}$$

The resistivity of No. *5* B. & S. wire, according to Table **13**, is *.000313* ohm per foot; since *3* such wires are used in parallel, the resistivity of the armature conductor in the present example is .000313 ÷ 3 = .000104 ohm per foot. The number of bifurcations in a bipolar machine is $n_p = 1$. Therefore, the armature resistance at *20°* C., from formula (**27**):

$$r_a = \frac{784 \times .000104}{4} = .0020 \text{ ohm.}$$

At *70°* C., the resistance is $\frac{70 - 20}{2\frac{1}{2}} = 20$ per cent. higher, or

$$r_a' = 1.20 \times .0020 = \mathbf{.0024} \text{ ohm.}$$

41. Example of Ring Armature.—*Find the resistance at* **150°** *F. of a* **12**-*pole ring armature which is wound with* **107** *sections, each of* **6** *turns of* **12** *strands of No.* **7** *B. & S. wire, if its dimensions are as follows: Diameter,* **106** *inches; length,* **26** *inches; radial thickness,* **5½** *inches; winding depth,* **¾** *inch.*

Solution.—The total number of inductors in this armature is 107 × 6 = *642;* hence by formula (**23**):

$$L_A = 642 \times \frac{2 \times 26 + 2 \times 5\frac{1}{2} + \frac{3}{4} \times \pi}{12} = 3{,}500 \text{ feet.}$$

From Table **13**, the resistivity of No. *7* wire is *.000497* ohm per foot; the value of ρ_f, therefore, as there are *12* wires in parallel in this case, is .000497 ÷ 12 = *.0000414*. The number of bifurcations in a multipolar machine being equal to the number of pairs of poles, we have from (**27**):

$$r_a = \frac{3{,}500 \times .0000414}{4 \times 6^2} = .001006 \text{ ohm at } 68° \text{ F.}$$

To find the resistance at 150° F. we must increase this value by $\frac{150 - 68}{4\frac{1}{2}} = 18.2$ per cent.; hence we have:

$$r_a = 1.182 \times .001006 = \mathbf{.00119} \text{ ohm.}$$

42. Check on Armature Calculation with Reference to Heating Limit.—The dimensions and the winding of the armature having been determined, it will be well, before going into the design of the magnet frame, to investigate whether the armature as designed fulfills the requirements as to its heating limit.

For this purpose we must determine the power losses due to the resistance of the winding, to hysteresis of the iron, and to the production of eddy currents in the core. The total loss being found, its ratio to the cooling surface of the armature determines the approximate rise of temperature of the armature.

If the latter is too high, the ratio of power loss to the cooling surface must be correspondingly decreased, either by increasing the cooling surface or by decreasing the power loss, or by a combination of both expedients. The cooling surface is increased by increasing the size of the armature, and at the same time the latter is enabled to accommodate a larger size of conductor, thus reducing its resistance and lowering the power loss in the winding.

An excessive rise of the temperature is usually the result of having assumed too great a winding depth; in re-designing the armature, particular attention should therefore be bestowed upon this point. The winding depth may be decreased either by reducing the number of layers of the armature wire, or by so subdividing the armature conductor that a suitable winding depth can be obtained by a proper rearrangement of the wires.

43. Power Consumed in Armature Winding.—The power lost in the armature winding of a dynamo or motor is the square of the current in the armature multiplied by the armature resistance, or in symbols:

$$w_a = C^2 \times r_a', \qquad (28)$$

where w_a = power dissipated in armature winding, in watts;

C = total current flowing in armature, in amperes;

r_a' = armature resistance, *warm*, in ohms.

In the case of a series machine, C in formula (**28**) is identical with the given external current; in shunt and compound-wound machines, however, allowance for the shunt excitation must be made. The amount of current passing through the shunt winding is the terminal E. M. F. of the machine divided by the resistance of the shunt circuit. The latter not having been determined at this stage of the design, the shunt current may be taken approximately from Table **18**:

TABLE 18.

APPROXIMATE SHUNT CURRENT IN SHUNT AND COMPOUND-WOUND DYNAMOS.

Capacity, in Kilowatts.	Shunt Current, in per cent. of Current Output.
.1	15% to 12%
.5	10 " 8
1	8 " 7
2.5	7 " 6
5	6 " 5
10	5 " 4
25	4 " 3
50 to 100	3 " 2.5
100 " 300	2.5 " 2
500 and over.	2 " 1.5

To obtain the current in the armature, the shunt current must be *added* to the desired current output, in case of a *generator;* and *deducted* from the given supply current, in case of a *motor.*

44. Power Lost by Hysteresis.—The hysteresis loss in the armature core is proportional to the frequency of reversal and to the mass of iron contained in the core:

$$w_h = \eta \times f \times M, \quad \ldots\ldots\ldots\ldots\ldots\ldots (29)$$

where w_h = hysteresis loss, in watts;

η = *hysteresis factor,* that is, the hysteresis loss in 1 cubic inch of iron at a frequency of 1 cycle per second, see Table **19**;

f = frequency, in cycles per second;

and M = mass of iron in armature core, in cubic inches.

The frequency is the number of revolutions per second multiplied by the number of pairs of magnet poles, or

$$f = \frac{n_1}{60} \times n_p \ldots\ldots\ldots\ldots\ldots\ldots \quad (30)$$

The mass, M, when allowing 10 per cent. of the core length for spaces between the laminæ, is given by the formula:

$$M = (D_a - B_a)\pi \times B_a \times .9L_a, \ldots\ldots\ldots\ldots\ldots (31)$$

TABLE 19.

HYSTERESIS FACTOR FOR DIFFERENT FLUX DENSITIES.

Density, in Lines per Square Inch. B_a.	Hysteresis Factor. Watts per Cu Inch. η.	Density, in Lines per Square Inch. B_a	Hysteresis Factor. Watts per Cu. Inch. η.	Density, in Lines per Square Inch. B_a.	Hysteresis Factor. Watts per Cu. Inch η.
10000	.0007	60000	.0128	82000	.0211
15000	.0014	61000	.0131	83000	.0215
20000	.0022	62000	.0135	84000	.0219
25000	.0031	63000	.0138	85000	.0223
30000	.0042	64000	.0142	86000	.0227
32500	.0048	65000	.0145	87000	.0232
35000	.0054	66000	.0149	88000	.0236
37500	.0060	67000	.0152	89000	.0240
40000	.0067	68000	.0156	90000	.0245
42500	.0074	69000	.0160	92500	.0253
45000	.0081	70000	.0164	95000	.0261
47500	.0088	71000	.0167	97500	.0275
50000	.0095	72000	.0171	100000	.0289
51000	.0098	73000	.0175	105000	.0312
52000	.0102	74000	.0179	110000	.0337
53000	.0105	75000	.0183	115000	.0362
54000	.0108	76000	.0187	120000	.0387
55000	.0111	77000	.0191	125000	.0414
56000	.0114	78000	.0195	130000	.0442
57000	.0117	79000	.0199	135000	.0470
58000	.0121	80000	.0203	140000	.0498
59000	.0124	81000	.0207	145000	.0527

where M = Mass of iron in armature core, in cubic inches;
D_a = diameter of armature core, in inches; for a toothed armature, D_a is the diameter at the root of the teeth;
B_a = radial thickness of armature core, in inches;
L_a = length of armature core, in inches.

In toothed armatures the hysteresis loss in the teeth, calculated by (**29**), in which the mass M is then that of the teeth, must be added to the hysteresis loss in the core.

The hysteresis factor η depends upon the magnetic density; its numerical value for any density is obtained in ergs per cubic centimetre by multiplying the 1.6th power of this density (expressed in lines per square centimetre) by the *hysteresis constant* or *coefficient of hysteresis* for the respective material; see Par. **262,** Book **13.** Practical values of η, in watts per cubic inch, for various flux densities in *sheet iron,* are given in Table **19.**

45. Power Lost by Eddy Currents.—The power consumed in setting up induced *eddy currents* in a body of iron subjected to reversing or varying magnetization increases with the square of the frequency and is proportional to the mass of the iron:

$$w_e = \varepsilon \times f^2 \times M, \qquad (\mathbf{32})$$

where w_e = eddy current loss, in watts;
ε = eddy current factor, or eddy current loss in 1 cubic inch of iron at a frequency of 1 cycle per second, see Table **20**;
f = frequency, in cycles per second, see formula (**30**);
M = mass of iron, in cubic inches, see formula (**31**).

The eddy current factor, ε, increases with the square of the flux density and with the square of the thickness of the sheets employed in building up the iron body. Table **20** gives the values of ε in watts per cubic inch at unit frequency for flux densities of from *10,000* to *145,000* lines per square inch, for sheet thicknesses of *.010*, *.020*, and *.040* inch.

TABLE 20.

EDDY CURRENT FACTORS FOR DIFFERENT FLUX DENSITIES AND THICKNESSES OF LAMINATION.

Density. Lines pr. sq. inch.	Eddy Current Factor, ε. Watts per cubic inch.			Density. Lines pr. sq. inch	Eddy Current Factor, ε. Watts per cubic inch.		
	Thickness of Lamination:				Thickness of Lamination:		
B$_a$	.010″	.020″	.040″	**B**$_a$	.010″	.020″	.040″
10000	.0000004	.000002	.000007	85000	.000030	.000121	.000483
20000	.000002	.000007	.000027	87500	.000032	.000128	.000513
30000	.000004	.000015	.000060	90000	.000034	.000136	.000542
40000	.000007	.000027	.000107	92500	.000036	.000143	.000573
45000	.000009	.000034	.000136	95000	000038	.000151	.000603
47500	.000010	.000038	.000152	97500	.000040	.000159	.000636
50000	.000011	.000042	.000167	100000	.000042	.000167	000669
52500	.000012	.000046	.000185	102500	.000044	.000176	.000703
55000	.000013	.000051	.000203	105000	.000046	.000184	.000737
57500	.000014	.000056	.000222	107500	000049	.000194	.000774
60000	.000015	.000060	.000241	110000	.000051	.000203	.000810
62500	.000017	.000066	.000262	112500	.000053	.000212	.000848
65000	.000018	.000071	·000282	115000	.000055	.000221	.000885
67500	.000019	.000076	.000305	117500	.000058	.000231	.000925
70000	.000021	.000082	.000328	120000	.000060	.000241	.000964
72500	.000022	.000088	.000352	125000	.000066	.000262	.001046
75000	.000024	.000094	.000376	130000	.000071	.000283	.001130
77500	.000025	.000101	.000402	135000	.000076	.000305	.001218
80000	.000027	.000107	.000428	140000	.000082	.000328	.001311
82500	.000029	.000114	.000456	145000	.000088	.000351	.001405

46. Specific Power Loss in Armature.—Having computed the power losses in the armature, their sum divided into the cooling surface gives the actual specific cooling surface of the armature, which, as stated in Par. **16**, should be between *.5* and *.75* square inch per watt for a drum armature, and between *.75* and *1.0* square inch per watt for a ring armature:

$$s = \frac{S_a}{w_a + w_h + w_e}, \ldots\ldots\ldots\ldots\ldots\ldots (33)$$

where s = specific cooling surface of armature;
S_a = cooling surface of armature, formula (**7**) or (**9**), respectively;
w_a = power lost in armature winding, formula (**28**);
w_h = “ “ “ hysteresis, “ (**29**);
w_e = “ “ “ eddy currents, “ (**32**).

If the value of s found by (**33**) is below *.5* for a drum, or below *.75* for a ring armature, the armature would heat up excessively, and should therefore be redesigned, as indicated in Par. **42**.

47. Temperature Increase of Armature.—Approximate limits of the temperature increase of practical armatures, as actually found for various values of the specific cooling surface s, are given in Table **21**. By means of

TABLE 21.

TEMPERATURE INCREASE OF ARMATURE FOR DIFFERENT SPECIFIC COOLING SURFACES.

Specific Cooling Surface. Sq. inches p. watt.	Temperature Increase.			
	Drum Armature.		Ring Armature.	
	Centigrade.	Fahrenheit.	Centigrade.	Fahrenheit.
.4	50° to 75°	90° to 135°	60° to 100°	108° to 180°
.5	45 “ 70	81 “ 126	55 “ 90	99 “ 162
.6	40 “ 60	72 “ 108	50 “ 80	90 “ 144
.7	35 “ 50	63 “ 90	45 “ 70	81 “ 126
.8	30 “ 45	54 “ 81	40 “ 60	72 “ 108
.9	25 “ 40	45 “ 72	35 “ 50	63 “ 90
1.0	20 “ 35	36 “ 63	30 “ 45	54 “ 81
1.25	15 “ 25	27 “ 45	25 “ 40	45 “ 72
1.5	10 “ 20	18 “ 36	20 “ 30	36 “ 54
2.0	5 “ 15	9 “ 27	15 “ 25	27 “ 45

this table the designer will be able to predict, from the result obtained by formula (**33**), the approximate rise of temperature in the armature.

48. Circumferential Current Density of Armature. —An excellent check on the heat calculation of the armature, and in many cases the only investigation made as to its heating properties, is the computation of the **circumferential current density,** that is, the total number of amperes carried per inch of the armature circumference. The circumferential current density is found by dividing the total number of amperes all around the armature by the core periphery:

$$c = \frac{N \times \frac{C}{2n_p}}{D_a \times \pi} = \frac{N \times C}{6.283 \times D_a \times n_p} \ldots\ldots\ldots\ldots\ldots (\mathbf{34})$$

c = circumferential current density, in amperes per inch of armature circumference;
N = total number of armature conductors;
C = total current at armature terminals, in amperes;
$2n_p$ = number of parallel circuits in armature winding;
D_a = diameter of armature core, in inches.

Having found c from (**34**), a comparison with Table **22,** compiled from actual machines of various types, gives an idea of the temperature increase that may be expected in the calculated armature when completed. By comparing the average increase derived from Table **22** with the average obtained from Table **21,** a very close approximation to the actual value of the temperature increase of the armature can usually be gained.

49. Example of Smooth-Drum Armature.—*A bipolar smooth-drum armature to produce* **40** *amperes at a constant E. M. F. of* **125** *volts when running at* **1,800** *revolutions per minute, has been calculated as follows: Diameter,* **5¾** *inches; length,* **9¼** *inches; radial depth of core discs,* **1⅛** *inches; winding,* **336** *conductors,* *No.* **9** *B. & S.; resistance (at 20° C.),* **.105** *ohm. Find the probable temperature increase.*

TABLE 22.

TEMPERATURE INCREASE OF ARMATURE CORRESPONDING TO DIFFERENT CIRCUMFERENTIAL CURRENT DENSITIES.

Circumferential Current Density. Amps. p. inch.	Temperature Increase of Armature.			
	High-Speed Dynamos.		Low-Speed Dynamos.	
	Centigrade	Fahrenheit	Centigrade.	Fahrenheit.
50 to 100	15° to 25°	27° to 45°	10° to 20°	18° to 36°
100 “ 200	20 “ 35	36 “ 63	15 “ 25	27 “ 45
200 “ 300	30 “ 50	54 “ 90	20 “ 35	36 “ 63
300 “ 400	40 “ 60	72 “ 108	25 “ 40	45 “ 72
400 “ 500	50 “ 70	90 “ 126	30 “ 45	54 “ 81
500 “ 600	60 “ 80	108 “ 144	35 “ 50	63 “ 90
600 “ 700	70 “ 90	126 “ 162	40 “ 60	72 “ 108
700 “ 800	80 “ 100	144 “ 180	50 “ 70	90 “ 126
800 “ 1000	....	....	60 “ 80	108 “ 144

Solution.—The warm resistance of this armature can be approximately taken as 1.16 × .105 = .122 ohm, see Par. **39.** The shunt current of a 5 K. W. dynamo, according to Table **18,** is between 5 and 6 per cent. of the terminal current; the total current, therefore, in this case is about 1.05 × 40 = **42** amperes. Hence, the power absorbed in the winding, by formula (**28**):

$$w_a = 42^2 \times .122 = \mathbf{214} \text{ watts.}$$

The frequency, from (**30**), is:

$$f = \frac{1800}{60} \times 1 = \mathit{30} \text{ cycles per second.}$$

The mass is found by (**31**):

$$M = (5\tfrac{3}{4} - 1\tfrac{7}{8})\pi \times 1\tfrac{7}{8} \times .9 \times 9\tfrac{1}{4} = \mathit{190} \text{ cubic inches.}$$

The flux density, $\mathbf{B}_a$, in the armature, is the flux divided by the armature cross-section. The flux in the present case is:

$$\Phi = \frac{6 \times 10^9 \times 1 \times 125}{336 \times 1800} = \mathit{1{,}240{,}000} \text{ lines, see } (\mathbf{21}),$$

and the cross-section of the armature:

$$2B_a \times .9L_a = 1.8 \times 1\tfrac{7}{8} \times 9\tfrac{1}{4} = \mathit{31} \text{ square inches.}$$

Hence we have:

$$\mathbf{B}_a = \frac{1{,}240.000}{31} = \mathit{40{,}000} \text{ lines per square inch;}$$

and, the hysteresis factor, from Table **19,** $\eta = .0067$. From (**29**) we therefore obtain the power absorbed by hysteresis:

$$w_h = .0067 \times 30 \times 190 = \mathbf{38} \text{ watts.}$$

The eddy current factor for a flux density of 40,000 lines per square inch, if the sheet iron used is .020 inch thick, is $\varepsilon = .000027$, according to Table **20,** consequently the power absorbed by eddy currents, from (**32**):

$$w_e = .000027 \times 30^2 \times 190 = \mathbf{5} \text{ watts.}$$

The approximate cooling surface of the armature, from (**7**), is:

$$S_a = 5\tfrac{3}{4}\, \pi \times 9\tfrac{1}{4} + (5\tfrac{3}{4})^2 \frac{\pi}{4} = 167 + 26 = \mathit{193} \text{ sq. in.}$$

Dividing S_a by the total power loss in the armature, the specific cooling surface is obtained, see (**33**):

$$s = \frac{193}{214 + 38 + 5} = \mathbf{.75} \text{ square inch per watt.}$$

The average temperature increase corresponding to this value, according to Table **21,** is about **40°** C.

By formula (**34**) the circumferential current density of the given armature is:

$$c = \frac{336 \times 42}{6.283 \times 5\tfrac{3}{4} \times 1} = \mathbf{390} \text{ amperes per inch.}$$

For this value of c, Table **22** gives an average of **50°** C. in the present case of a high-speed machine.

Taking the mean of the two averages found, we obtain $\frac{1}{2}(40 + 50) = \mathbf{45°}$ C. as the approximate average temperature rise of the armature.

The armature here considered is that of a machine in actual use. It has a temperature rise of *42°* C. when running continuously at full load.

50. Example of Toothed Ring Armature.—*It is assumed that the design of a toothed ring armature for a* **4***-pole* **330** *K. W. compound-wound railway generator for an output of* **600** *amperes at* **550** *volts, when running at a speed of* **400** *revolutions per minute, has resulted in the following data: External diameter of core,* **44½** *inches; internal diameter,* **21½** *inches; length,* **25** *inches; radial depth of solid portion,* **9¾** *inches; number of slots,* **90**; *width of slots, ⅞ inch; depth of slots,* **1¾** *inches; winding,* **4** *copper strips, ½ inch by ¼ inch, per slot; armature resistance, at 20° C.,* **.0087** *ohm. Required to predetermine the approximate rise of the armature temperature.*

Solution.—

Warm resistance: $r_a' = 1.16 \times .0087 = \mathit{.0101}$ ohm;

Total current (Table **18**): $C = 1.02 \times 600 = 612$ amps;

∴ Power absorbed by armature winding, formula (**28**):

$$w_a = 612^2 \times .0101 = \mathbf{3{,}780} \text{ watts.}$$

Frequency, formula (**30**): $f = \frac{400}{60} \times 2 = \mathit{13.33}$ cycles;

Diameter at roots of teeth: $44\frac{1}{2} - (2 \times 1\frac{3}{4}) = \mathit{41}$ inches.

Mass of body, formula (**31**):

$$M = (41 - 9\tfrac{3}{4})\,\pi \times 9\tfrac{3}{4} \times .9 \times 25 = \mathit{21{,}537} \text{ cu. in.}$$

Mass of teeth, Fig. 19:

$$\left[(44\tfrac{1}{2})^2\,\frac{\pi}{4} - (41)^2\,\frac{\pi}{4} - 90 \times 1\tfrac{3}{4} \times \tfrac{7}{8}\right] \times .9 \times 25 = 2{,}400 \text{ cu. in.};$$

Flux per pole, formula (**21**):

$$\Phi = \frac{6 \times 10^9 \times 550}{(90 \times 4) \times 4.0} = \mathit{22{,}971{,}000} \text{ lines;}$$

Cross-section of body: $1.8 \times 9\frac{3}{4} \times 25 = \mathit{438}$ sq. ins.;
Cross-section at roots of teeth opposite one pole :

$$\frac{41 \times \pi - 90 \times \frac{7}{8}}{4} \times .9 \times 25 = \mathit{277} \text{ sq. ins.;}$$

Flux density in armature body:
  22,917,000 ÷ 438 = 52,300 lines per square inch;
Flux density in teeth:
  22,917,000 ÷ 277 = *83,000* lines per square inch;
Hysteresis factor for body (Table **19**): $\eta = .0103;$
Hysteresis factor for teeth (Table **19**): $\eta = .0215;$

∴ Power loss by hysteresis:

$$w_h = .0103 \times 13.33 \times 21{,}537 + .0215 \times 13.33 \times 2{,}400$$
$$= 2{,}960 + 690 = \mathbf{3{,}650} \text{ watts.}$$

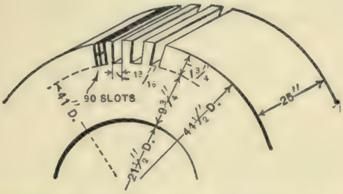


FIG. 19.—DIMENSIONS OF 330 K W. TOOTHED RING ARMATURE.

Supposing the iron used in this armature is *.015* inch thick. Since the eddy current loss is proportional to the square of the thickness, and since $.015'' = \frac{3}{2} \times .010''$, we must multiply the factor found in Table **20** for .010″ iron at the given flux density by $(\frac{3}{2})^2$, or by $\frac{9}{4}$. The eddy current factor for 52,300 lines and .010″ iron is *.000012;* hence, for .015″ iron, $\varepsilon = .000012 \times \frac{9}{4} = \mathit{.000027}$. Similarly for 83,000 lines (density in teeth), $\varepsilon \doteq .000030 \times \frac{9}{4} = \mathit{.000068}$.

∴ Power loss by eddy currents:

$w_e = 000027 \times 13.33^2 \times 21{,}537 + .000068 \times 13.33^2 \times 2{,}400$
$= 104 + 29 = \mathbf{133}$ watts.

Cooling surface (Fig. 19):

$S_a = (44\frac{1}{2} - 11\frac{1}{2})\pi \times 2(25 + 11\frac{1}{2}) = \mathit{7560}$ square inches;

Total energy loss in armature:

$3{,}780 + 3{,}650 + 133 = \mathit{7{,}563}$ watts;

∴ Specific cooling surface, by (**33**):

$s = 7{,}560 \div 7{,}563 = \mathit{1.0}$ square inch per watt.

The average rise of temperature corresponding to $s = 1$, from Table **21,** is **37½**° C.

Circumferential current density, by (**34**):

$$c = \frac{(90 \times 4) \times 612}{6.283 \times 44\frac{1}{2} \times 2} = \mathbf{394} \text{ amperes per square inch.}$$

Average temperature increase corresponding to $c = 394$, from Table **22,** for high-speed dynamo, **50**° C.

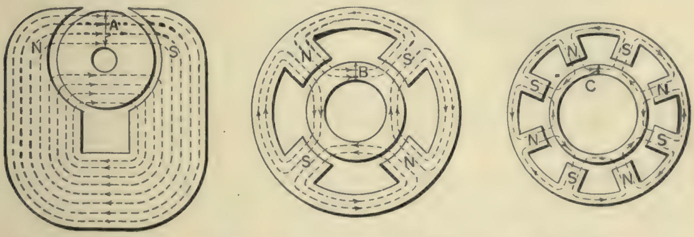
Mean of the two averages: $\frac{1}{2}(37\frac{1}{2} + 50) = \mathbf{44}°$ C.

The actual rise of the temperature in this armature, which is that of an existing machine, is about *45*° C.

THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS.

DESIGN OF FIELD MAGNET.

51. General Form of Field Magnet.—With a given size (diameter and length) of armature the value of the total flux, Φ, does not necessarily depend upon the form of the field magnet. This is shown by comparing Figs. 20, 21, and 22, in which armatures of equal size are represented in bipolar, four-pole, and eight-pole fields. Assuming that in all three cases the polepieces cover a like portion of the armature periphery, then the total number of magnetic lines entering and leaving the surface of the armature is the same in the three designs. This is evident when it is considered that by the above assumption the total number of square inches covered by the polepieces in Figs. 21 and 22 is equal to those in Fig. 20, and that each square inch contains the same number of lines at the given flux density. In practice the flux density is usually less in bipolar than in multipolar machines, but



FIGS. 20, 21, AND 22.—ARMATURES OF EQUAL SIZE IN BIPOLAR, FOUR-POLE, AND EIGHT-POLE FIELDS.

this difference is not a necessity and need not be considered in the preliminary determination.

It is generally known whether the machine is to have two poles or more, but in any case it is an advantage for the designer to be free to alter the form of the field magnet without being obliged to change the general dimensions of the armature, although the relative diameter would ordinarily be made greater for a multipolar machine. The last-named fact, however, need not increase the surface of the armature required for carrying the conductors and getting rid of the heat generated in them.

This brings us to the consideration of the comparative advantages of bipolar and multipolar field magnets, which is a much-discussed question. Prior to 1890, the bipolar construction was generally employed for all direct-current machinery, but since that time the multipolar form has been adopted by nearly all manufacturers in this country and in Europe, for sizes down to about *5* or *10* K. W., and even below this for low-speed machines. In England, however, it is still common practice to build bipolar generators and motors as large as *100* or *200* K. W.

52. Advantages and Disadvantages of Multipolar Machines.—The *advantages* of multipolar dynamos are the following:

(1) Saving in weight of material for both armature and field magnet;

(2) More compact and symmetrical form;

(3) Better ventilation of armature and field magnets;

(4) For armatures of the same diameter, the individual parts of the field frame are much smaller and more easily handled in the multipolar than in the bipolar type.

The *disadvantages* of multipolar machines are:

(1) Greater complication, owing to the increased number of parts and connections;

(2) Strong magnetic side pull on armature, even when only slightly nearer one polepiece than another; much greater than in bipolar field;

(3) With multiple circuit armature windings (Figs. 14 and 15), the flux must be the same for each pole, otherwise the E. M. F. of the circuits will be unequal, producing wasteful currents in them, which, in turn, cause excessive sparking and heating. This difficulty is not present in two-circuit windings (Fig. 16), using only two sets of brushes.

The saving in material is clearly shown by comparing Figs. 20 and 21. In the former, it will be seen that the armature must carry ½ the total flux between its shaft and periphery, while in Fig. 21 the armature cross-section is only required to carry ¼ the total flux, hence the radial depth *B* of the armature core in Fig. 21 need be only one-half as great as *A* in Fig. 20. This allows the core of the four-pole machine to be hollowed out as shown in Fig. 21, thus reducing its weight. It will be observed that the bulk of the field magnet is also less for the multipolar than for the bipolar construction.

The difference is still more marked when we compare the eight-pole machine in Fig. 22 with the bipolar type in Fig. 20. In Fig. 22 the radial thickness of the field ring is only ½ as much as in Fig. 21, and ¼ as great as the thickness of the yoke in Fig. 20, and the armature may be hollowed out to a radial thickness, *C*, of only ¼ that of the bipolar armature, *A*, as shown, the total flux being the same for all three designs. The external diameters of the armatures being the same, it follows that an equal number of similar inductors can be carried in each case. In short, the capacity of the multipolar machines in Figs. 21 and 22, considered either as generators or motors, is as great as that of the bipolar form in Fig. 20, although the volume of material is decidedly less for the multipolar types.

53. Proper Number of Poles for Multipolar Field Magnets.—In the case of a machine of considerable size, for which a multipolar field would almost surely be adopted, the next step is to decide upon how many poles it is best to employ. This is a question partly of selecting a size and number of field cores, coils, etc., convenient for making and handling, but it is chiefly a matter of the number of *magnetic cycles* per second occurring in the armature core. If we consider any particular cubic inch of the iron forming this core, it is evident that its magnetism is reversed once for each pole that it passes. A complete cycle of magnetic changes takes place in passing a north and a south pole, hence the number of cycles per second is the number of *pairs* of poles passed in one second, that is,

$$f = \frac{n_1 \times n_P}{60} \dots\dots\dots\dots\dots\dots (\mathbf{35})$$

In this expression, f is the number of cycles per second, corresponding to the **frequency** of an alternating current; n_1 is the speed of the armature, in revolutions per minute; and n_P is the number of *pairs* of field magnet poles.

Direct-current machinery is designed, generally, so that f is between *10* and *35* cycles per second. This limits the number of poles, the object being to reduce the core losses, that is, the losses due to *hysteresis* and *eddy currents* in the armature, the former, as we have seen in Par. **44**, being proportional to f, whereas the latter increase with the square of f, Par. **45**. The lower frequency of about *10* or *15* cycles applies to low-speed machines for direct connection to engines, etc., and the higher frequency of *30* or *35* is adopted in high speed, belt-connected generators and motors.

By transformation of (**35**), it follows that the maximum speed of a *four-pole* machine (*2* *pairs* of poles) should be

$$n_1 = \frac{60 \times f}{n_P} = \frac{60 \times 35}{2} = \mathbf{1050} \text{ revs. per min.}$$

In some instances, four-pole machines are run at higher speeds than this; for example, *1200* revs. per min., which gives *40* cycles. But this is rather too high a frequency, and should not be adopted except for special reasons.

If the values $n_p = 1, 2, 3, 4$, etc., and $f = 10, 15, 25$, and 35 be inserted in the above formula for n_1, the following table of dynamo speeds for various numbers of poles is obtained. From this table the proper number of poles for low, medium, and high speed machines of given speeds can be readily taken.

TABLE 23.

NUMBER OF MAGNET POLES FOR VARIOUS SPEEDS.

Number of Poles.	Limits of Speeds.		
	Low Speed Machines. $f = 10$ to 15.	Medium-Speed Machines. $f = 15$ to 25.	High Speed Machines $f = 25$ to 35.
2	600 to 900	900 to 1500	1500 to 2100
4	300 “ 450	450 “ 750	750 “ 1050
6	200 “ 300	300 “ 500	500 “ 700
8	150 “ 225	225 “ 375	375 “ 525
10	120 “ 180	180 “ 300	300 “ 420
12	100 “ 150	150 “ 250	250 “ 350
14	85 “ 130	130 “ 215	215 “ 300
16	75 “ 115	115 “ 190	190 “ 260
18	70 “ 100	100 “ 170	170 “ 230
20	60 “ 90	90 “ 150	150 “ 210
24	50 “ 75	75 “ 125	125 “ 175

Generally speaking, the *bipolar type* is used for high speeds, such as *1500* revs. per min. or more. A further reason for selecting the bipolar type for very high speeds is the fact that machines running at 1,500 revolutions, or more, are usually quite small. For speeds between *400* and *900* revs. per min. the *four-pole* construction is especially suitable, giving frequencies from *13⅓* to *30* cycles. This includes nearly all belted dynamos and motors, from the large sizes of *200* K. W., or more, down to about *10* K. W., below which the bipolar form is generally used for the reasons given. Between *200* and *400* revs. per min. *6 poles* are commonly adopted, the corresponding frequencies being from *10* to *20* cycles. This range of speed comprises practically all generators directly connected to high-speed engines, from the largest to the smallest, excepting combinations with very high speed engines of *600* revs. per min., or more, for which *4* poles would be preferable. When a dynamo is directly driven by a steam turbine, at an extremely high speed without reducing gear, the field should be of the bipolar type. For speeds below *200* revs. per min. the number of poles is generally increased to *8* or more. This applies to most generators directly connected to low-speed engines.

In some cases motors of various sizes, even down to *1* or *2* H. P., are required to run at low speeds in order to be connected directly to the machines which they drive. For this purpose *6 poles* are suitable for speeds from *200* to *400* revs. per min., and *8 or more poles* if the speed is below *200* revs. per min. Electric railway motors are nearly always constructed with *4* poles, the speed being very variable, but having a maximum value in most cases of about *800* revs. per min. This gives a rather high frequency of $26\frac{2}{3}$ cycles, but, as the maximum speed is rarely maintained for more than a few minutes at a time, the heating due to hysteresis and eddy currents in the armature core does not rise above the limit allowed. The average speed corresponds to a moderate frequency of *15* to *20* cycles.

54. Sectional Area of Magnet Frame.—The proper number of poles having been decided upon, the next step is to find the approximate size of the field magnet required in a given case.

The cross section of the field magnet is determined by the total flux which it has to carry, sufficient area being allowed to avoid excessive flux density in the iron. The probable flux in the armature being given by (**21**), it is necessary to make the cross-section of the field cores, and other portions of the field magnet, large enough to carry this useful flux *plus the leakage lines* which do not pass through the armature.

The number of leakage lines is usually from *10* to *50* per cent. of the useful flux for *bipolar toothed-armature* machines. With *bipolar smooth-core* armatures the leakage is considerably greater, ordinarily amounting to from *25* to *100* per cent., according to the size and type of the machine. Hence, the total flux of a bipolar machine is from *1.10* to *2.00* times the useful flux, this multiplier being called the **leakage factor** (see Par. **55**). For *multipolar machines* the general form that has been adopted almost universally is the *ring type*, represented in Figs. 21 and 22 ; with this form of field magnet the leakage factor ranges from *1.08* to *1.20* in case of a *toothed* armature, and from *1.15* to *1.50* in case of a *smooth* armature, according to the size (see Table **24**).

Denoting the leakage factor by λ, it follows from the preceding that the cross-section of the field magnet is:

$$S_m = \frac{\lambda \times \Phi}{\mathbf{B}_m} = \frac{6 \times 10^9 \times n_p \times E \times \lambda}{N \times n_1 \times \mathbf{B}_m} \text{ sq. ins.,} \ldots. \mathbf{(36)}$$

where all symbols have the same meaning as in (**21**), and $\mathbf{B}_m$ is the flux density in the field magnet. The latter should be taken between *80,000* and *100,000* lines per square inch for *wrought iron* and *cast steel,* and between *40,000* and *50,000* lines per square inch for *cast iron.*

In case of *bipolar* machines, S_m is the cross-section of one core; but for multipolar machines, since Φ is the sum of the lines which enter the armature from all the north poles, S_m is the total cross-section of all the north poles, and must therefore be divided by the number of pairs of poles, n_P, in order to give the area of one core.

The *yoke,* or other part connecting the cores, should have a cross-section of $\frac{S_m}{n_P}$ square inches, if it carries all the lines of one south pole to one of the north poles, as in Figs. 20 and 23; or it should have a sectional area of $\frac{S_m}{2n_p}$ square inches, if one-half the lines of each south pole are carried by it to the next north pole on one side, and the other half to the next north pole on the other side, as is the case with the types shown in Figs. 21, 22, and 24.

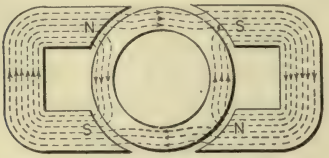


FIG. 23.—FOUR-POLE TYPE, IN WHICH THE YOKE CARRIES ALL THE LINES FROM ONE POLE.

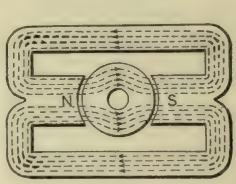


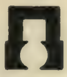
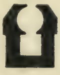
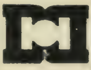
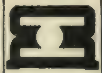
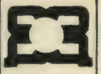
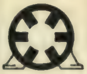
FIG. 24.—BIPOLAR TYPE, IN WHICH THE YOKE CARRIES HALF THE LINES FROM ONE POLE.

55. Factor of Magnetic Leakage.—In Table **24** the usual values of the leakage factor for the types of machines most commonly employed for direct-current dynamos are compiled. The *higher* values for each size refer to the most unfavorable conditions as regards magnetic leakage. namely, to a *smooth-core* armature, to a massive magnet frame with *cast iron polepieces,* and to *high speed.* The *lower* values in each case are for the most favorable magnetic conditions brought about by the employment of a *toothed armature,* a *wrought iron* or *cast steel* field frame, and *low speed.* With *toothed* armatures, the length of the air gap is much less than for smooth-core armatures, hence the gap reluctance is smaller than for a corresponding machine having a smooth armature, and therefore the leakage is proportionately diminished. The use of *wrought iron* or *cast steel* for the field frame has the effect of materially reducing the areas of the leakage paths without much affecting their lengths; the leakage of a wrought iron or cast steel machine is consequently less than that of a cast iron machine, other conditions being the same. In case the machine is designed for *low speed,* its armature will be proportionately larger, and its leakage, therefore, is reduced to that for a correspondingly larger output. In machines of small capacity, the employment of a *ring* instead of a *drum* armature likewise increases the size of the armature and reduces the leakage.

The fact that the leakage factor decreases with the size of the machine is due to the difficulty, or rather impossibility, of advantageously dimensioning the magnetic circuit in small machines. In these the length of the air gaps is comparatively much larger, and the distance of the leakage surfaces much smaller, than in large dynamos; the reluctance of the air gaps, therefore, is relatively much larger, while the reluctances of the leakage paths are considerably smaller, comparatively, than in large machines. Since each of these causes will individually effect a greater leakage, it is evident that their combined result will produce a high value of the leakage factor for a small dynamo.

TABLE 24.

LEAKAGE FACTORS FOR VARIOUS TYPES AND SIZES OF DYNAMOS.

Capacity of Dynamo, in Kilowatts.	Ordinary Horseshoe Type. 	Inverted Horseshoe Type. 	Double Magnet Type. 	Bipolar Iron Clad Type. 	Fourpolar Iron Clad Type. 	Multipolar Ring Type. 
.1	1.50 to 2.00	1.40 to 1.75	——	1.25 to 1.50	——	——
.25	1.45 · 1.80	1.35 · 1.60	1.45 to 2.00	1.22 · 1.40	——	——
.5	1.40 · 1.70	1.30 · 1.50	1.40 · 1.90	1.20 · 1.35	——	——
1	1.35 · 1.65	1.25 · 1.45	1.35 · 1.80	1.18 · 1.30	——	——
2.5	1.30 · 1.60	1.20 · 1.40	1.30 · 1.70	1.16 · 1.28	1.35 to 1.75	1.20 to 1.50
5	1.25 · 1.55	1.18 · 1.35	1.25 · 1.60	1.14 · 1.25	1.32 · 1.65	1.18 · 1.40
10	1.22 · 1.50	1.16 · 1.30	1.20 · 1.55	1.12 · 1.22	1.30 · 1.60	1.16 · 1.35
25	1.20 · 1.45	1.14 · 1.25	1.18 · 1.50	1.10 · 1.20	1.28 · 1.55	1.15 · 1.32
50	1.18 · 1.40	1.12 · 1.22	1.16 · 1.45	1.09 · 1.18	1.26 · 1.50	1.14 · 1.30
100	1.16 · 1.35	1.10 · 1.20	1.15 · 1.40	1.08 · 1.15	1.24 · 1.45	1.13 · 1.28
200	1.14 · 1.30	——	——	——	1.22 · 1.40	1.12 · 1.25
300	1.12 · 1.25	——	——	——	1.20 · 1.35	1.11 · 1.22
500	——	——	——	——	——	1.10 · 1.20
1000	——	——	——	——	——	1.09 · 1.18
2000	——	——	——	——	——	1.08 · 1.15

56. Length of Magnet Cores.—The length of the magnet cores must be chosen so as to provide sufficient space for the field winding, without, on the other hand, making the length of the magnetic path excessive; or, since the latter consideration usually predominates over the former, the cores should be made as short as possible without increasing the thickness of the winding to an undue amount.

In *bipolar* machines with *toothed* armatures the length of each field core is usually about *1* to *1½* times the core diameter for *small sizes*, in which the diameter of the magnets is from *2* to *5* inches. For *larger sizes*, up to *18* or *20* inches diameter, the length of the magnet cores is ordinarily from ¾ to *1¼* times the core diameter; and for diameters above *20* inches, the length is from *10* to *33* per cent less than the diameter. In the case of a bipolar *smooth-core* armature, the length of the field magnet is about *50* per cent. greater than for a corresponding bipolar *toothed* armature, to give more space for the additional winding required by the larger air gap.

In *multipolar smooth-armature* machines, the usual practice is to make the length of the magnet cores from ½ to *1¼* times their diameter; for *large* machines the length is chosen between ½ and ¾ of the diameter; for *medium-sized* machines between ¾ and *1*; and for *small* machines between *1* and *1¼* times the diameter. For *toothed-armature* machines the length of the cores is made from ⅔ to ¾ that of a corresponding smooth-armature dynamo.

57. Length of Air Gap.—The air gap is made small with toothed armatures, being determined by the following conditions:

1. Sufficient mechanical clearance for free rotation;
2. Avoidance of eddy currents in the pole faces, explained in connection with Figs. 2 and 3, page 8;
3. Reduction of side pull on armature, especially in multipolar fields (see Par. **52**);
4. Sufficient distance between armature core and pole surface to overcome armature reaction.

63).

As a result of the above considerations, the length of the air gap with toothed armatures is made from $\frac{1}{16}$ inch in *small bipolar* machines to $\frac{1}{4}$ or $\frac{1}{2}$ inch in *large multipolar* ones.

For *smooth-core* armatures the air gap is necessarily greater than for a corresponding toothed armature, as it includes the height of the winding as well as a proper mechanical clearance, which ranges from $\frac{3}{32}$ inch in *small* machines to $\frac{5}{8}$ inch in *large* ones.

TABLE 25.

RADIAL CLEARANCE BETWEEN ARMATURE AND POLEPIECES.

Diameter of Armature, in inches.	Smooth-Core Armature.		Toothed or Perforated Armature.
	Drum.	Ring.	
2	$\frac{3}{32}$"	..	$\frac{1}{16}$
4	$\frac{1}{8}$	$\frac{3}{32}$	$\frac{5}{64}$
8	$\frac{5}{32}$	$\frac{1}{8}$	$\frac{3}{32}$
12	$\frac{3}{16}$	$\frac{5}{32}$	$\frac{1}{8}$
18	$\frac{7}{32}$	$\frac{3}{16}$	$\frac{5}{32}$
24	$\frac{1}{4}$	$\frac{7}{32}$	$\frac{3}{16}$
30	$\frac{9}{32}$	$\frac{1}{4}$	$\frac{7}{32}$
40	..	$\frac{9}{32}$	$\frac{1}{4}$
50	..	$\frac{5}{16}$	$\frac{9}{32}$
75	..	$\frac{3}{8}$	$\frac{5}{16}$
100	..	$\frac{7}{16}$	$\frac{11}{32}$
125	..	$\frac{1}{2}$	$\frac{3}{8}$
150	..	$\frac{9}{16}$	$\frac{7}{16}$
200	..	$\frac{5}{8}$	$\frac{1}{2}$

Table **25** gives the clearances usually allowed for various types and sizes of armatures. For toothed and perforated armatures the figures given are at the same time the lengths of the air gaps, but for smooth armatures the clearance must be added to the height of the winding space given in Table **14**, in order to obtain the length of the air gap.

58. Example.—*Determine the approximate size and form of field magnet required for an armature,* **12** *inches in diameter and* **10½** *inches long, to run at* **1,200** *revolutions per minute.*

Solution.—With this size and speed, either the bipolar or the four-pole construction may be adopted. Let us consider both cases, taking the bipolar type first.

We will assume that it was found in calculating this armature that the flux required to cause the desired output is $\Phi = 5{,}000{,}000$ lines. This, as can be found by means of formula (**22**), would make the field density about

$$\mathbf{B}_g = \frac{5{,}000{,}000}{1.3 \times 12 \times 10\tfrac{1}{2}} = 30{,}500 \text{ lines per square inch,}$$

which is a good value for an armature of the given size.

The usual leakage factor for this size of *bipolar* smooth-armature machine is about $\lambda = 1.40$; consequently, the total flux in the field magnet will be

$$\Phi' = 1.4 \times 5{,}000{,}000 = 7{,}000{,}000 \text{ lines.}$$

The cores in the present case will preferably be made of *wrought iron*, for which the average practical flux density is $\mathbf{B}_m = 90{,}000$; hence, the required cross-section of the field magnet:

$$S_m = \frac{\Phi}{\mathbf{B}_m} = \frac{7{,}000{,}000}{90{,}000} = 77.8 \text{ square inches.}$$

If circular cores are used, their diameter should consequently be:

$$D_m = \sqrt{S_m \times \frac{4}{\pi}} = \sqrt{77.8 \times 1.273} = \mathbf{10} \text{ inches.}$$

The approximate length of the magnets, in the case of an armature with a *toothed* core, according to Par. **56**, is between ¾ and 1¼ times the diameter, if the latter is between 5 and 20 inches. In the present example we will take a multiplier somewhat smaller than the average of the figures given above, say .9, and we have:

$$L_m = 10 \times .9 = \mathbf{9} \text{ inches.}$$

In case of a *smooth* armature, this length should be increased by 50 per cent., for the reason stated in Par. **56**; consequently for the smooth-armature design:

$$L_m = 9 \times 1.5 = \mathbf{13\tfrac{1}{2}} \text{ inches.}$$

59. Bipolar Design.—To lay off the complete magnetic circuit, draw the pole faces AB and CD in Fig. 25, making each an arc of about 135°, corresponding to a polar embrace of 75 per cent. The distance at which these arcs are placed from the 12-inch circle representing the armature depends upon whether the latter has a *toothed* or a *smooth* core. In the former case, the air gap EF should

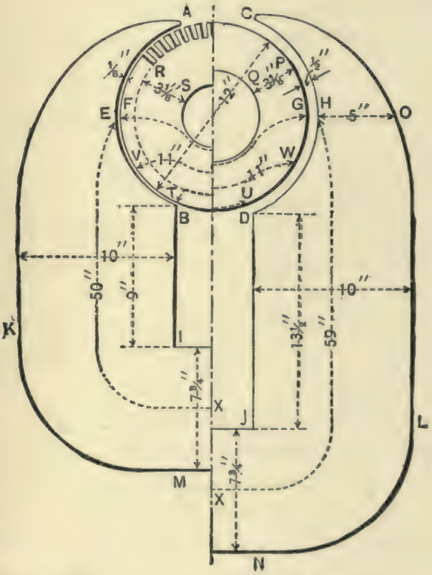


FIG. 25.—MAGNETIC CIRCUIT OF BIPOLAR MACHINE.

be made about ⅛ inch, whereas in the latter case *GH* should be either about ½ inch for a *ring* armature, or about ¾ inch for a *drum* (compare with Tables **14** and **25**).

The lines *BI* and *DJ* are then drawn vertically downward from the points *B* and *D*, a distance equal to the length of the cores, which, since wrought iron polepieces are used, is 9 inches or 13½ inches, according to whether the armature has a toothed or a smooth core, respectively. The diameters *IK* and *JL* are made equal to D_m, which has been found to be 10 inches. In Fig. 25 the toothed-core design is shown at the left side of the center line and the smooth-core design at the right side, so that a comparison can be made at a glance.

The *yoke* of a bipolar machine is usually made of rectangular cross-section having a breadth equal to the diameter of the cores. Its height *IM* or *JN* should therefore in this case be $\frac{77.8}{10} = \mathbf{7\frac{3}{4}}$ inches, provided the same material is employed as for the cores. The cross-section of the yoke is thus made equal to that of the cores, and is kept practically uniform throughout; whereas the polepieces may be tapered, as shown, so that the middle section at *HO* is about ⅔ as large as the core-section, or about

$$\frac{\frac{2}{3} \times 77.8}{10\frac{1}{2}} = \mathbf{5} \text{ inches}$$

thick, the divisor 10½ being the length of the polepieces, which is equal to that of the armature. If the distribution of the lines in the air gaps were uniform, only ½ the total flux would pass through the section *HO*; but when the field is distorted by armature reaction, the flux in the upper half of one of the polepieces may increase to about ⅔ of the total amount.

The *radial depth* of the armature core required to carry the flux Φ is:

$$B_a = \frac{5,000,000}{2 \times 80,000 \times 10\frac{1}{2} \times .95} = \mathbf{3\frac{1}{8}} \text{ inches,}$$

when a flux density of 80,000 lines per square inch of armature cross-section is taken, and when 5 per cent. of the length is allowed for insulation between the armature laminæ. With a *smooth* core this dimension is laid off at PQ, and in a *toothed* armature at RS. This fixes the internal diameter at

$$12 - (2 \times 3\tfrac{1}{8}) = 12 - 6\tfrac{1}{4} = \mathbf{5\tfrac{3}{4}} \text{ inches,}$$

in the former, and

$5\frac{3}{4}$ inches *minus twice the depth of the teeth*

in the latter case.

It will thus be noted that the effect of putting slots in the armature core, or of varying their depth, is to correspondingly change the internal diameter of the armature. With a *drum* winding this makes no material difference in the design, but with a *ring* winding it is essential to provide sufficient space for the winding to pass through the interior, and also to leave room for the shaft and spider which carry the armature. If the space left after deducting B_a and twice the depth of the slots from the external diameter is found too small for the above purposes, an increase in the internal diameter is necessary which would raise the density of the lines in the armature if the design were left unaltered. To avoid an excessive flux density from this cause, the external diameter of the armature must be correspondingly enlarged, with the consequence of increasing the distance BD between the field cores, and of lowering the flux density in the air gap.

60. Four-Pole Design.—If the armature given in Par. **58** is to run in a four-pole field, the armature flux would be the same as before, if the flux density in the air gaps and the polar embrace were the same. In multipolar machines the former is usually somewhat greater, and the latter a little less, than in bipolar machines, hence we will assume that the armature flux is 5,000,000 lines, as in

Par. **58.** The leakage factor, however, is smaller for a multipolar dynamo than for a bipolar machine of equal output; see Pars. **54** and **55.** For a four-pole machine of the size under consideration the average value of λ is about 1.25 instead of 1.40, which it was in the bipolar design. The field flux required for the four-pole frame will therefore be about

$$\Phi' = 1.25 \times 5{,}000{,}000 = \mathbf{6{,}250{,}000} \text{ lines.}$$

Each field core carries one-half of the total flux, because all the useful lines enter the armature from the two pole-pieces of north polarity, and pass to the two south-poles; hence each core must carry 3,125,000 lines. If composed of wrought iron or cast steel, a flux density of 90,000 lines per square inch may be allowed, requiring a sectional area of

$$S_m = \frac{3{,}125{,}000}{90{,}000} = \mathbf{34.7} \text{ square inches.}$$

The corresponding diameter is:

$$D_m = \sqrt{34.7 \times 1.273} = \mathbf{6\tfrac{5}{8}} \text{ inches.}$$

The *length* of the magnets in case of a *smooth*-armature machine, according to Par. **56,** is approximately:

$$L_m = 6\tfrac{5}{8} \times .85 = \mathbf{5\tfrac{5}{8}} \text{ inches,}$$

and in case of a *toothed*-armature machine:

$$L_m = 5\tfrac{5}{8} \times .7 = \mathbf{4} \text{ inches.}$$

In Fig. 26, the field cores for the toothed armature are drawn to scale at *BI,* at the left side of the center line, and for the smooth armature at *DJ,* at the right side, as in Fig. 25.

The *yoke* in the four-pole design carries but half the lines of each magnet, hence its cross-section need only be one-half the area of one magnet core, or 17.4 square inches. Making the frame **8** inches wide, which gives a flange, or overlap, of $\frac{11}{16}$ inch on either side of the cores in the direction of the shaft, the radial thickness *IM* or *JN* of the yoke will be $17.4 \div 8 = 2.2$, which we will raise to **2½** inches to allow for rounding the corners of the yoke-section.

With the same armature flux, the *radial depth* of the armature core is one half as great in Fig. 26 as it is in Fig. 25, since in the four-pole design the armature flux is split up into four circuits, while in the bipolar frame there are only two flux paths through the armature (see Par. **52**). Therefore *PQ*, for a smooth core, and *RS*, for a toothed armature, is made $3\frac{1}{8} \div 2 = \mathbf{1\frac{9}{16}}$ inches, which determines the internal diameter. The air gap is left the same as before, being ⅛ inch for a *toothed* armature and ½ inch for a *smooth ring* core.

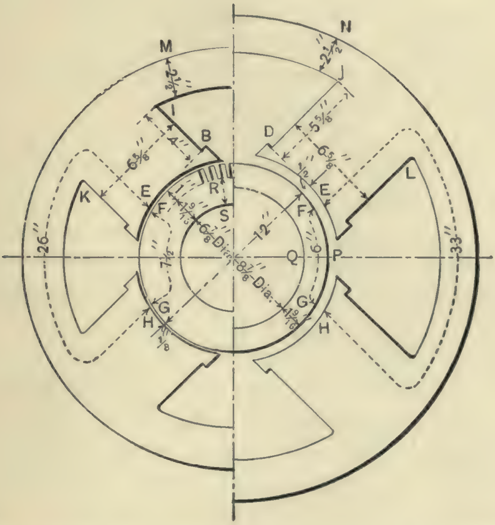


FIG. 26.—MAGNETIC CIRCUIT OF FOUR-POLE MACHINE.

61. **Form of Magnet Cores.**—In the preceding paragraphs it has been assumed that the field cores were simple cylinders having a straight axis and a circular cross-section. This is ordinarily and preferably the case.

Any departure from a circular cross-section is objectionable for the following reasons:

1. The circle has the least circumference for a given area, even the perimeter of an equivalent square being about 12 per cent. longer; and a rectangle with one side three times the length of the other, has a perimeter nearly 30 per cent. greater than that of a circle of equal area.
2. It is much easier to make a cylinder, since the pattern and core itself can be turned in a lathe.
3. Cylindrical spools for the coils are more easily made than elliptical or rectangular ones.
4. The operation of winding is much more difficult with a rectangular or elliptical core, since the strain on the wire is very unsteady.
5. A rectangular, or even an elliptical, core is much more likely to cause a short-circuit between the turns of wire, since they are forced together at certain points and are liable to cut through the insulation.

Similar arguments apply to a core having a curved axis, that is, those having ring or bow-shaped field-magnet cores. These latter are far more difficult to wind, and possess little or no compensating advantage. The shortness of magnetic circuit which is claimed for them is very doubtful, for the reason that the actual length of core required for equal average depth of winding is greater than if it were straight, since the winding on the inner side of the curve is higher than on the outer side. It often happens that, in the design of dynamos, it is apparently desirable to adopt a core which is not circular in section, or has a curved axis; but it is better to change the entire design in order to avoid these forms, except, perhaps, for a special machine to fit in a certain limited space.

In the case of multipolar magnets of the ring type shown in Figs. 21 and 22, the inner ends of the cores form the pole faces; and since it is desirable for the latter to be rectangular rather than circular, in order to have as much surface as possible, it is a common practice to make the cores rectangular also. But when the pole faces are extended by casting or attaching polepieces to the cores, as in Fig. 26, the latter should have a circular section.

CALCULATION OF MAGNETIZING FORCE.

62. Total Magnetizing Force.—The number of ampere-turns required to produce the necessary flux through the magnetic circuit is the sum of the ampere-turns required to overcome the reluctances of the various parts of the circuit and of the ampere-turns needed to counteract the effect of the armature reaction on the magnetic field. The formula for the total magnetizing force, therefore, is:

$$AT = at_g + at_a + at_m + at_r \ldots\ldots\ldots\ldots \textbf{(37)}$$

in which AT = total number of ampere-turns required;
at_g = ampere-turns necessary to overcome the reluctance of the air gaps;
at_a = ampere-turns to overcome reluctance of armature core;
at_m = ampere-turns to overcome reluctance of magnet frame;
at_r = ampere-turns necessary to compensate for armature reaction (Book **15**, Pars. **56** to **65**).

63. Magnetizing Force Required for any Part of a Circuit.—Each of the three terms at_g, at_a and at_m in the above formula (**37**) can be obtained from the law of the magnetic circuit stated in Par. **35**, Book **15**:

$$Flux = \frac{Magnetomotive\ Force}{Reluctance},$$

which can also be written in the form:

$$Magnetomotive\ Force = Flux \times Reluctance \ldots \textbf{(38)}$$

According to Par. **32**, Book **15**, the reciprocal of *reluctance* is called *permeance*, hence

$$Magnetomotive\ Force = \frac{Flux}{Permeance}.$$

But the permeance, that is, the magnetic conductance, of a path may be expressed by the permeability of the material and the dimensions of the magnetic path, just as the electric conductance of a body is its conductivity times its area, divided by its length; consequently we have:

$$Permeance = Permeability \times \frac{Area}{Length}.$$

Inserting this expression of the permeance into (**38**), we obtain

$$Magnetomotive\ Force = \frac{Flux \times Length}{Permeability \times Area},$$

and since the quotient of flux by area is the magnetic flux density **B**, we have

$$Magnetomotive\ Force = \frac{Density}{Permeability} \times Length,$$

or

$$\text{M. M. F.} = \frac{\mathbf{B}}{\mu} \times L \ldots\ldots\ldots\ldots\ldots \textbf{(39)}$$

From (**39**) the magnetomotive force is obtained in *gilberts*, if the density **B** is expressed in lines per square centimetre and the length L, in centimetres; hence, according to Par. **34**, Book **15**:

$$\begin{aligned} Ampere\text{-}turns &= .796 \times gilberts \\ &= .796 \times \frac{Density}{Permeability} \times Length, \end{aligned}$$

or in symbols, practically:

$$at = .8 \times \frac{\mathbf{B}}{\mu} \times L \ldots\ldots\ldots\ldots \textbf{(40)}$$

If the length of the path is given in inches, and the flux density in lines per square inch, we have:

$$\textit{Length in cm.} = 2.54 \times \textit{Length in inches},$$
$$\text{or } L = 2.54 \times L'',$$
$$\textit{Lines per square cm.} = \frac{\textit{Lines per square inch}}{6.45},$$
$$\text{or } \mathbf{B} = \frac{\mathbf{B}''}{6.45},$$

in which the inch mark ($''$) is used as an index to designate the quantities expressed in English measure.

Substituting the above values, formula (**40**) becomes:

$$at = .8 \times \frac{\mathbf{B}''}{6.45\mu} \times 2.54\, L'' = .313 \times \frac{\mathbf{B}''}{\mu} \times L'' \ldots (\mathbf{41})$$

The permeability of air being practically 1, the ampere-turns required to overcome the reluctance of the air gap are:

$$at_g = .313 \times \mathbf{B}_g'' \times l_g'', \ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{42})$$

in which $\mathbf{B}_g''$ is the flux density per square inch of gap area, and l_g'' is the length in inches of the magnetic paths in both air gaps.

Since $\frac{\mathbf{B}}{\mu}$ in (**39**) is the magnetizing force, **H**, in gilberts per centimetre, it follows that $.313 \times \frac{B''}{\mu}$ in (**41**) is the expression for the magnetizing force, in ampere-turns, required per inch length of the circuit in order to cause a flux density of $\mathbf{B}''$ lines per square inch. Designating this *specific magnetizing force* in English units by $\mathbf{H}''$, we have:

$$at = \mathbf{H}'' \times L'' \ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{43})$$

In practice, *magnetization curves* are used in which the values of the specific magnetizing force $\mathbf{H}''$, corresponding to various densities $\mathbf{B}''$, are plotted for the different kinds of iron employed, so that the calculation of the ampere-turns for any part of a magnet circuit resolves itself into the very simple operation of finding from the curve the specific magnetizing force $\mathbf{H}''$ for the particu-

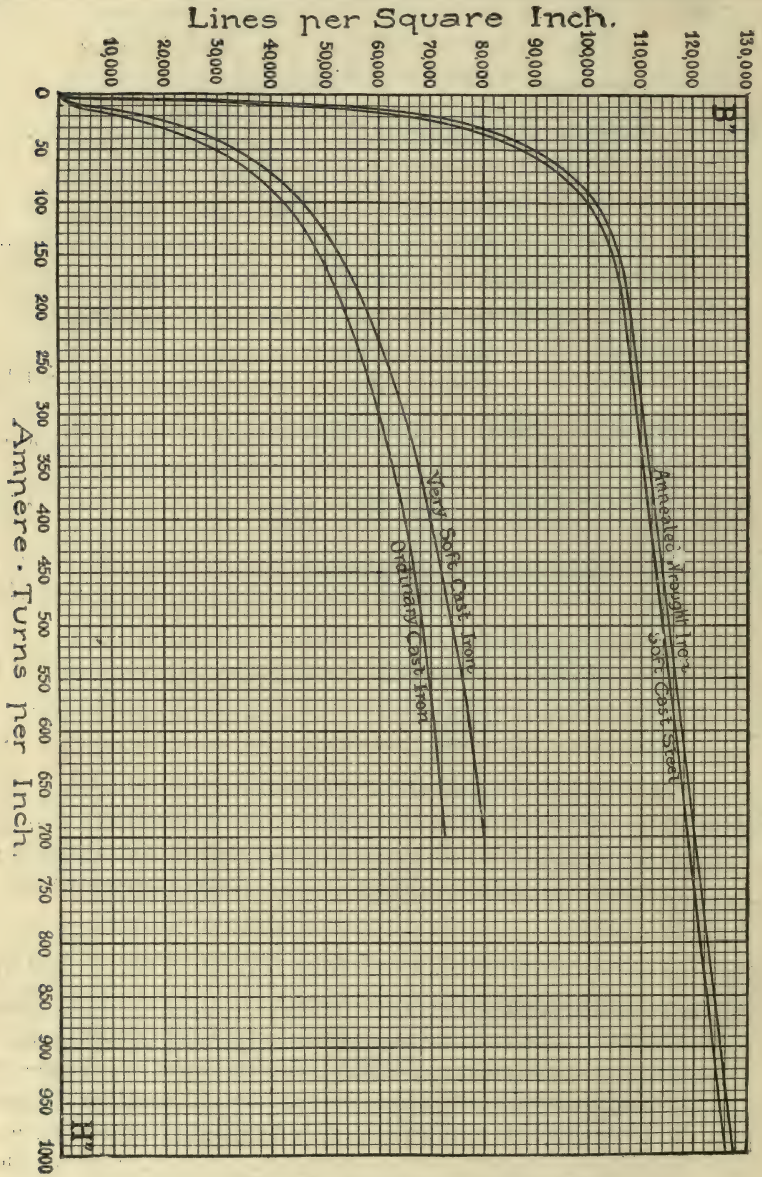


FIG. 27.—MAGNETIZATION CURVES.

lar kind of iron used and for the flux density employed in that part of the circuit, and in multiplying the value so found by the mean length of the magnetic path in the

TABLE 26.

SPECIFIC MAGNETIZING FORCES FOR VARIOUS DENSITIES IN DIFFERENT MAGNETIC MATERIALS.

Flux Density B″ Lines per sq. in.	Ampere-Turns per Inch Length of Circuit, H″.			
	Annealed Wrought Iron.	Soft Cast Steel.	Very Soft Cast Iron.	Ordinary Cast Iron.
5,000	1.7	2.8	10	13
10,000	2.2	3.7	14	19
15,000	2.7	4.3	18	24
20,000	3.5	5	24	31
25,000	4.5	5.8	31	40
30,000	5.5	6.6	42	50
35,000	6.5	7.6	54	65
40,000	7.5	8.8	72	88
45,000	8.5	10	95	116
50,000	9.6	12	128	160
55,000	11	14	170	222
60,000	13	16	230	295
65,000	16	19	300	400
70,000	20	23	400	570
75,000	25	27	525	...
80,000	31	34	700	...
85,000	40	44	...	...
90,000	51	57	...	...
95,000	67	75	...	...
100,000	91	100	...	...
105,000	137	160	...	...
110,000	290	325	...	...
115,000	500	550	...	...
120,000	700	750	...	...
125,000	900	950	...	...
130,000	1100	1150	...	...

part of the circuit under consideration. In this manner the values of at_m and at_a in (**37**) can be obtained, the former by one single operation if the field frame is all of the same material, or by adding several products if various portions of the magnet frame are made of different materials.

The exact calculation of the compensating ampere-turns, at_r, is shown in Par. **65**; for preliminary calculation of the magnetizing force, however, it is sufficient to increase the sum of the gap, armature, and frame ampere-turns by *15* or *20* per cent., to make up the demagnetizing tendency due to armature reaction.

64. Magnetization Curves.—In Fig. 27 the magnetization curves are given for *cast iron, wrought iron,* and *cast steel,* the values being averaged from tests of various brands of each kind of iron. These curves are well adapted for the student's use, but the practical dynamo designer will obtain closer results by using curves plotted particularly for the iron which he employs. For the convenience of the student the values contained in Fig. 27 are given in Table **26**.

65. Magnetizing Force for Compensating Armature Reactions.—The armature current, in magnetizing the armature core, exerts a double influence upon the magnetic circuit: (1) a *direct* weakening influence upon the magnetic field, due to the lines of force set up by the armature winding, and (2) an *indirect,* secondary influence by shifting the magnetic field in the direction of the rotation in case of a generator, and in the opposite direction in case of a motor, thereby causing greater magnetic density to take place in those portions of the polepieces at which the armature leaves the pole than in those at which it enters.

The *direct* weakening effect of the armature current, or the number of field ampere-turns which are neutralized by the influence of the armature current, is equal to the *back* *ampere-turns*, or those within the demagnetizing belt; see Par. **61**, Book **15.** This demagnetizing number of ampere-turns is equal to $\frac{1}{360}$ of the total armature turns multiplied by twice the angle of the brush lead, or:

$$at_r' = \frac{N' \times C}{2n_p} \times \frac{\alpha}{180}, \qquad\qquad (\mathbf{44})$$

in which N' = total number of turns on armature;
C = current flowing in armature;
$2n_p$ = number of parallel armature circuits;
α = angle of field distortion, or angle of brush lead.

The number of armature turns, N', is equal to the number of armature conductors, N, in case of *ring-wound* armatures, and equal to one half the number of conductors in case of *drum-wound* armatures.

The angle of field distortion in a *smooth-core* armature is approximately equal to half the angle between two adjacent pole corners. In *toothed* and *perforated* machines, the weakening effect of the armature magnetomotive force is checked by the presence of iron surrounding the conductors, this checking influence being the stronger the greater the ratio of tooth section to field density, that is, the smaller the tooth density. The angle of lead in *toothed* armatures is from *.3* to *.9* times the half-pole-angle, and for *perforated* machines from *.2* to *.8* times that angle, according to the flux density in the teeth. For the tooth densities usually employed in practical machines, the above formula (**44**) should be multiplied by $\frac{1}{2}$ or $\frac{2}{3}$ for toothed armatures, and by $\frac{1}{3}$ or $\frac{1}{2}$ for *perforated* armatures.

The *indirect* influence of the armature field, due to the greater magnetizing force required on account of the increased flux density in the armature teeth and polepieces, depends upon the material of, and the average density in, the polepieces. The number of ampere-turns required to compensate for the indirect effect is usually from *25* to *100* per cent. of direct compensating ampere-turns; hence, the total number of compensating ampere-turns is from 1.25 to 2 times the direct compensating ampere-turns and can therefore be expressed by the formula:

$$at_r = k \times \frac{N' \times C}{2n_p} \times \frac{\alpha}{180}, \ldots\ldots\ldots\ldots\ldots\ldots (45)$$

in which k is a factor which usually varies from *1.25* to *2.00*, as follows:

k = 1.25 to 1.75, *average 1.5,* for *wrought iron* and *cast steel* polepieces;
k = 1.50 to 2.00, *average 1.75*, for *cast iron* polepieces.

The average of k for *wrought iron* and *cast steel* corresponds to a mean flux density of about 105,000 lines per square inch; the lower limit is for 80,000 lines, or less, and the upper figure given refers to a density of about 120,000 lines per square inch. For *cast iron* the average corresponds to a mean density in the polepieces of about 45,000 lines per square inch; the minimum corresponds to 20,000 lines, or less. and the maximum is to be taken when the average density in the polepieces is about 60,000 lines per square inch.

66. Calculation of Ampere-Turns for Bipolar Smooth-Armature Dynamo.—The various dimensions of the magnetic circuit of the machine represented at the right in Fig. 25 having been determined, the ampere-turns required in the field coils are calculated as follows:

The number of ampere-turns needed to overcome the reluctance of the two air gaps is obtained from **(42)**, in which for the present case $\mathbf{B}_g'' = 30{,}500$ lines per square inch (see page 72), and $l_g'' = 2 \times \frac{1}{2} \times 1.25 = 1\frac{1}{4}$ inches. The average length of the magnetic lines in the gaps is here taken 25 per cent. greater than twice the distance across from polepiece to armature core, because. when the machine is carrying current in the armature, the lines do not pass straight across in the direction of the radius, but are more or less inclined to the latter, owing to the distortion of the field. We therefore have:

$$at_g = .313 \times 30{,}500 \times 1\tfrac{1}{4} = \mathit{11{,}930} \text{ ampere-turns.}$$

The ampere-turns needed to overcome the armature reluctance are obtained from (**43**). In order to find the average length, l_a'', of path for the lines in the armature, the longest line, *FG*, and the shortest line, *TU*, are drawn as indicated by dotted lines in Fig. 25. The average length, *VW*, is then laid off midway between them. In Fig. 25 the lines *FG*, *TU*, and *VW* are not continuous, because the armature shown to the left, being a toothed armature, has a smaller internal diameter than that on the right, which is a smooth armature. In the present case the right side of Fig. 25 is to be considered only; in speaking of lines *FG*, *TW*, and *VW*, therefore, the left half of the armature is supposed to be symmetrical to the right half, so that the dotted lines in the two halves meet at the center line. By measuring the continuous line *VW* so obtained, the average length of the path in the armature is found to be about 11 inches. The flux density in the armature core was taken at 80,000 lines per square inch (see page 75); the specific magnetizing force for wrought iron having this density is $\mathbf{H}_a'' = 31$ ampere-turns per inch, according to Fig. 27 or to Table **26**. Consequently, the armature magnetizing force:

$$at_a = 31 \times 11 = \mathit{340} \text{ ampere turns.}$$

The ampere-turns needed to overcome the field magnet reluctance are calculated by substituting in (**43**) the respective values of l_m'' and $\mathbf{H}_m''$ for the magnet frame. The length of path, *HXE*, Fig. 25, is found by measurement to be about 59 inches. The flux density $\mathbf{B}_m''$ was fixed at 90,000 lines per square inch (see page 72), for which the specific magnetizing force, by Table **26**, is $\mathbf{H}_m'' = 51$, the material of the cores and yoke being wrought iron. Hence,

$$at_m = 51 \times 59 = \mathit{3{,}010} \text{ ampere-turns.}$$

The compensating ampere-turns, since the average density in the wrought iron polepieces is less than 80,000 lines per square inch, are, according to formula (**45**),

$$at_r = 1.25 \times \frac{125 \times 240}{2} \times \frac{22\frac{1}{2}}{180} = \mathit{2,350} \text{ ampere-turns.}$$

It is here assumed that the machine under consideration is a generator of about 125 volts and 240 amperes output, the number of armature conductors being determined by transposing formula (**21**), page 41, thus:

$$N = \frac{6 \times 10^9 \times n_p \times E}{\Phi \times n_1} = \frac{6 \times 10^9 \times 1 \times 125}{5,000,000 \times 1200} = 125.$$

The pole space angle, in laying out Fig 25, was assumed to be 180° − 135° = 45°, half of which is taken as the angle of brush lead in the above formula.

Summing up the above magnetizing forces, according to (**37**), we obtain:

$$\begin{array}{lrl} at_g & = 11,930 & \text{ampere-turns for air gaps;} \\ at_a & = 340 & \text{" " armature;} \\ at_m & = 3,010 & \text{" " magnet frame;} \\ at_r & = 2,350 & \text{" " armature reaction.} \\ \hline AT & = \mathbf{17,630}, & \text{total ampere turns required.} \end{array}$$

67. Calculation of Ampere-Turns for Bipolar Toothed-Armature Dynamo.—The calculation in Par. **66** applies to a *smooth* armature; if a *toothed* core armature were adopted, the required magnetizing force would be less, as follows:

The air gap is smaller in a toothed machine, being ⅛ inch in the present case instead of ½ inch. The length of the path in air, therefore, is ¼ inch for the toothed armature. The gap density, however, is greater if the armature flux remains the same, owing to the concentration of the lines by virtue of the teeth. Adding about 50 per cent. to the previous value of the gap density, we obtain $\mathbf{B}_g'' = 45,000$ lines per square inch. Hence, we find that the gap magnetizing force for the toothed armature is:

$$at_g = .313 \times 45,000 \times \tfrac{1}{4} = \mathit{3,520} \text{ ampere-turns.}$$

The cores are only 9 inches long instead of 13½, hence, the path in the frame is 9 inches shorter, or $l_m'' = 50$ inches, and we have:

$$at_m = 51 \times 50 = \mathit{2,550} \text{ ampere-turns.}$$

The compensating ampere-turns are also less in the case of a toothed armature, since the angle of field distortion is smaller; taking $\alpha = 12°$, we obtain:

$$at_r = 1.25 \times \frac{125 \times 240}{2} \times \frac{12°}{180} = \mathit{1,250} \text{ ampere-turns.}$$

The number of armature ampere-turns, however, is greater for a toothed than for a smooth armature, because the flux in the teeth is higher than that in the solid portion of the core. Assuming a tooth density of 120,000 lines per square inch, which is often employed, the specific magnetizing force for the teeth would be 700 ampere-turns per inch (see Table **26**), and if the slots are 1 inch deep the tooth ampere-turns would be:

$$at_a' = 700 \times 2 = \mathit{1,400} \text{ ampere-turns.}$$

For the remaining 9 inches of the path, the flux density is 80,000 lines per square inch, as before, hence the magnetizing force required for the solid portion of the armature core

$$at_a'' = 31 \times 9 = \mathit{280} \text{ ampere-turns.}$$

The total number of armature ampere-turns for the toothed armature, therefore, is:

$$at_a = 1,400 + 280 = \mathit{1,680} \text{ ampere-turns,}$$

instead of 340, as in the case of the smooth armature.

The total magnetizing force required in case of the toothed armature, consequently, is:

$$AT = 3,520 + 2,550 + 1250 + 1,680 = \mathbf{9,000} \text{ ampere-turns,}$$

as against *17,630* ampere-turns for the smooth-armature machine.

68. Calculation of Ampere-Turns for Four-Pole Smooth-Armature Dynamo.—Referring to Fig. 26, the mean lengths of the path for the smooth-armature design are as follows: $l_g'' = 1.25$ inches (the gap distance of $2 \times \frac{1}{2}$ inch being increased by 25 per cent. to allow for distortion), $l_a'' = 6$ inches, and $l_m'' = 33$ inches. The pole space angle in this case is $22\frac{1}{2}°$, one-half of which is about 11°. Therefore, the magnetizing forces required in the different parts of the circuit:

$$\begin{aligned} at_g &= .313 \times 30{,}500 \times 1.25 &&= 11{,}930 \text{ ampere-turns;} \\ at_a &= 31 \times 6 &&= 190 \quad \text{"} \\ at_m &= 51 \times 33 &&= 1{,}680 \quad \text{"} \\ at_r &= 1.25 \times \frac{125 \times 2 \times 240}{4} \times \frac{11°}{180} &&= 1{,}150 \quad \text{"} \\ \text{Total magnetizing force: } AT &= &&\overline{\mathbf{14{,}950}} \quad \text{"} \end{aligned}$$

In the formula for at_r, the number of turns must here be multiplied by 2, because in a four-pole machine there are 4 parallel armature circuits, hence in formula (**21**) the number of pairs of circuits has the value $n_p = 2$.

69. Calculation of Ampere-Turns for Four-Pole Toothed-Armature Dynamo.—For the toothed-armature design the lengths are $l_g'' = \frac{1}{4}$ inch, $l_a'' = 7\frac{1}{2}$ inches, and $l_m'' = 26$ inches; and the angle of brush lead is about 6°; hence, we have:

$$\begin{aligned} at_g &= .313 \times 45{,}000 \times \tfrac{1}{4} &&= 3{,}520 \text{ ampere-turns;} \\ at_a' &= 700 \times 2 &&= 1{,}400 \quad \text{"} \quad \text{"} \\ at_a'' &= 31 \times 5\tfrac{1}{2} &&= 170 \quad \text{"} \quad \text{"} \\ at_m &= 51 \times 26 &&= 1{,}330 \quad \text{"} \quad \text{"} \\ at_r &= 1.25 \times \frac{250 \times 240}{4} \times \frac{6}{180} &&= 630 \quad \text{"} \quad \text{"} \\ \text{Total magnetizing force: } AT &= &&\overline{\mathbf{7{,}050}} \text{ ampere-turns.} \end{aligned}$$

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THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS.

CALCULATION OF MAGNET WINDING.

70. Series, Shunt, Compound, and Differential Field Winding.—Having found the total number of ampere-turns required to cause the necessary flux through the magnet frame, the final calculation of the field winding consists in determining the proper number of turns and amperes which, when multiplied together, will produce the desired magnetizing force. The determination of the strength of the current passing through the field winding, and, consequently, the selection of the size of the field wire, depends upon the method of field excitation employed.

There are four methods of winding the magnets of continuous-current machines, the *series*, *shunt*, *compound*, and *differential winding*, each of which has distinct advantages which make its use preferable for certain purposes.

Series winding is used chiefly for constant-current arc-light generators and for street railway motors, but in the latter case, though the field winding as a whole is in series with the armature, the separate coils can be variously connected in series or in parallel with each other, so as to vary their resistance and magnetizing effect. Series winding is sometimes adopted for motors applied to hoisting and other purposes where very variable speed is required. Series motors may also be used for driving fans, pumps, or other machines in which the load is fairly constant and is positively connected by direct coupling or gearing, so that the motor speed cannot become excessive, as it would tend to do if a belt slipped off.

Shunt winding is almost universally employed in motors for constant speed with variable load. Shunt-wound generators were formerly used for giving constant voltage for electric light, power, and railway purposes, but at present *compound-wound generators* have largely taken their place, since the latter automatically maintain a constant, or even slightly rising, voltage with increase of load.

Compound winding, besides being used for most generators, is further applied to motors when a strong starting torque is required.

Differential winding is applicable to generators that are required to produce a fairly constant voltage with wide variations in speed, as, for example, those driven by windmills, or by the axles of railway cars for electric train lighting. Differential winding is also employed in motors required to run with very constant speed at varying load.

In any given case there is generally little difficulty in deciding which of the four methods of field winding should be adopted, the custom being well defined regarding generators and motors for each purpose.

71. Determination of the Magnet Winding.—The method of winding being decided upon, the next step is to find the proper size of wire to employ for the field coils. It is obvious that a given number of ampere-turns may consist of a few turns carrying a large current, or of a great number of turns carrying a small current.

Whether the former or latter arrangement is employed depends upon the method of field excitation of the dynamo. In a *series machine* the total armature current traverses the field coils; hence the field winding consists of few turns of a conductor having a comparatively large current capacity. In a *shunt dynamo,* on the other hand, only a very small portion of the total current flows through the field winding; the latter must, therefore, consist of many turns of fine wire. *Compound* and *differential machines,* finally, have a series winding as well as a shunt winding, *assisting* each other in the former, and *opposing* each other in the latter; the total excitation, therefore, is the *sum* of the series and shunt ampere-turns in one case, and their *difference* in the other. The methods employed for determining the number of turns and the size of wire for the various kinds of field windings are given in the following paragraphs **72** to **74**.

72. Calculation of Series Winding.—The field winding of a series machine being always fed by the total current generated or supplied, which has a definite value, the required number of turns, T, is immediately found by dividing the ampere-turns, AT, by the given value, C, of the current; thus:

$$T = \frac{AT}{C} \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(46)}$$

The size of wire must be sufficient to carry the given current C without overheating and without causing an undue loss of power in the magnets. This condition is usually fulfilled by providing a conductor area of from *1,000* to *2,000* circular mils per ampere. For series dynamos furnishing a constant current of 10 amperes, the usual current output of series arc-lighting machines, the size of the magnet wire has been found by experience to be between $\frac{1}{10}$ and $\frac{1}{8}$ inch in diameter—that is, No. *10*, No. *9*, or No. *8* B. & S. gauge, depending upon the depth of the winding and the temperature limit prescribed. For the usual range of temperature rise employed, which is from *20°* to *50°* C., the specific cooling surface of the magnet coils should be from 4 to 1½ square inches per watt, respectively, as follows:

For a rise of 20° C. allow about 4 square inches per watt;
" " " " 25° " " " 3½ " " " "
" " " " 30° " " " 3 " " " "
" " " " 40° " " " 2 " " " "
" " " " 50° " " " 1½ " " " "

73. Calculation of Shunt Winding.—In the determination of the best size of wire for a shunt winding, the quantities known are the ampere-turns required and the voltage by which the shunt winding is supplied—that is, the voltage of the machine. One of the simplest methods is based upon the fact that the resistance of one mil-foot of commercial copper—that is, the resistance of one foot of a copper wire, one mil, or one-thousandth of inch, in diameter—is almost exactly *12* ohms at 60° C., which is about 35° C. above the average machine-room temperature. Hence, the resistance of any conductor of commercial copper at 60° C. is

$$R = \frac{12 \times l'}{d^2},$$

in which l' is the length of the wire, in feet, and d^2 its sectional area in circular mils. Or, since $12 \times l'$ is the length of the wire in inches, we can write

$$R = \frac{l''}{d^2}, \quad \ldots\ldots\ldots\ldots\ldots\ldots \ldots (47)$$

in which l'' is the length of the wire *expressed in inches.* The current flowing in the above wire is, by Ohm's Law,

$$C = \frac{E}{R} = \frac{E \times d^2}{l''}.$$

It is also evident that the ampere-turns in any shunt winding are numerically equal to the amperes that would result if a single turn of the magnet wire were supposed to be subjected to the given voltage, because two turns would have twice the resistance and take one-half the current; three turns would have three times the resistance and therefore take one-third the current; and so on for any number of turns. Since the current flowing in a shunt circuit is the terminal E. M. F. divided by the shunt resistance, we have therefore:

$$\text{Ampere-turns} = \frac{\text{Voltage}}{\text{Resistance of One Turn}}.$$

Expressing the resistance according to formula (**47**), this becomes:

$$\text{Ampere-turns} = \frac{\text{Voltage} \times \text{Circular Mils}}{\text{Length of One Turn in inches}},$$

or in symbols:

$$AT = \frac{E \times d_m^2}{l_t''}, \quad \ldots\ldots\ldots\ldots\ldots (48)$$

where E = terminal voltage of machine;
d_m = the diameter of the magnet wire, in mils;
and l_t'' = mean length of one turn, in inches.

By transposition of (**48**) we obtain the cross-section of the magnet wire required:

$$d_m^2 = \frac{AT \times l_t''}{E'}, \quad \ldots\ldots\ldots\ldots\ldots (49)$$

in which AT = total magnetizing force required, in ampere-turns;
l_t'' = average length of one turn of wire in magnets, in inches;
E' = voltage between terminals of shunt winding.

In applying the above formula to a shunt winding for a generator, allowance must be made for the resistance of the rheostat, which is put in the shunt circuit to regulate the E. M. F. This resistance will consume a portion of the voltage amounting to from 10 to 20 per cent. Therefore, the voltage E' substituted in the formula should be 10 to 20 per cent. lower than the E. M. F. of the machine.

For a multipolar machine, E' in the above formula is the voltage corresponding to *one set* of coils. Thus, if all the coils are connected *in series*, and if there are *two* coils in each magnetic circuit, the value of E' in a *four-pole* machine is *one-half* the machine-voltage (diminished by 10 or 20 per cent. in case of a generator); in a *six-pole* machine, E' is *one-third;* in an *eight-pole* dynamo, *one-fourth* of the terminal voltage, etc. In the case that the field coils are connected *in groups* across the machine terminals, the proper value of E' is found by multiplying the number of coils constituting one magnetic circuit by the number of parallel groups, and dividing the product so obtained by the total number of coils on the machine; the result is the factor by which the terminal voltage of the machine must be multiplied. For example, if the shunt winding of a 12-pole ring type 125-volt generator is connected in 4 groups of 3 magnets each, the above factor will be $\frac{2 \times 4}{12} = \frac{2}{3}$, hence $E' = \frac{2}{3}(125 - 12\frac{1}{2}) = 75$ volts. If in the same machine all the magnets were connected in parallel, that is to say, if the number of groups were 12, we would have $\frac{2 \times 12}{12} = 2$, and the shunt voltage per magnetic circuit would be $E' = 2 \times 112\frac{1}{2} = 225$ volts.

The size of wire obtained by formula (**48**) will furnish the required number of ampere-turns irrespective of the number of turns employed. If a small number of turns is chosen, the current will be high; and if a large number of turns is used, the current will be small. If the current is too high, the wire will become overheated and may eventually burn out. If the shunt current is taken too small, the magnet winding will become too bulky and the cost of the machine unnecessarily great in consequence. It is therefore seen that it is very important to determine the proper strength of the shunt current in each case.

Designating the watts consumed in the magnet winding by w_m, the shunt current can be expressed as

$$C_{sh} = \frac{w_m}{E'}.$$

Since in this equation E' is known, being the terminal voltage of the machine diminished by 10 to 20 per cent. to allow for the drop due to the regulating resistance, the problem remains to find the proper value of w_m. The power which can be dissipated in the field winding depends upon the cooling surface of the magnets and upon the temperature rise permitted. If the cooling surface of the magnet coils is denoted by S_M, and the allowable temperature increase by t, in Centigrade degrees, the power dissipated in the magnet winding is given by

$$w_m = \frac{t}{75} \times S_M. \qquad \textbf{(50)}$$

the average temperature increase with a power dissipation of 1 watt per square inch of exposed coil surface being about 75° C.

Inserting the value of w_m given by (**50**) into the above equation for C_{sh}, the following formula for the shunt current is obtained:

$$C_{sh} = \frac{t \times S_M}{75 \times E'}, \qquad \ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{51})$$

in which t = prescribed temperature increase of magnets, in degrees C., being usually limited to 50°;

S_M = cooling surface of magnets, in square inches.

The values of l_t and S_M, in formulas (**49**) and (**51**) respectively, depend upon the height of the magnet winding, which at this stage of the calculation is not yet known. We must, therefore, temporarily make an assumption of its magnitude. For this purpose the average practical height of the winding on magnets of different sizes is given in Table ***27***, page 98. The winding height of a *cylindrical* magnet is obtained by taking the figure given under the heading of "*Circular Cores*" for the nearest diameter given in the first column. In case of a *rectangular* or *oval* magnet, the figure corresponding to the nearest cross-section given in the second column is taken. Thus, to find the height of the winding space of a rectangular magnet, *4* by *6* inches, the nearest area given in the second column is *28.3* square inches; hence, the required winding height is *2* inches in case of a bipolar machine, and *2¾* inches in case of a multipolar machine.

The two columns added at the right give the ratios of the length of the mean turn to that of the diameter, and, of course, only apply to circular magnets. These ratios are tabulated in preference to the actual lengths of the average turn, in order to enable the ready application of the table to diameters intermediate to those given. The approximate length of the mean turn for a cylindrical magnet of any diameter between 1 and 36 inches can be directly taken from the table by multiplying the diameter of the core under consideration by the ratio given for the nearest diameter in the respective one of the two last columns. For instance, if the diameter of the core is 6⅝ inches, the ratios for the 6-inch core are taken and the mean turn is found:

$$l_t'' = 6\tfrac{5}{8} \times 3.93 = \mathbf{26} \text{ inches,}$$

if the machine is of a *bipolar* type; and

$$l_t'' = 6\tfrac{5}{8} \times 4.32 = \mathbf{28.6} \text{ inches,}$$

in case of a *multipolar* type.

TABLE 27.

HEIGHT OF WINDING SPACE FOR DYNAMO MAGNETS.

Size of Magnet Core.		Height of Winding Space, inches.				Ratio of Mean Turn to Diameter of Circular Cores.	
		Circular Cores.		Rectangular or Oval Cores.			
Diameter, inches.	Cross-Section, sq. ins.	Bipolar.	Multipolar.	Bipolar.	Multipolar.	Bipolar.	Multipolar.
1	.8	½	¾	..	..	4.71	5.50
2	3.1	¾	1¼	1	1½	4.32	5.11
3	7.1	1	1¾	1¼	2	4.19	4.97
4	12.6	1¼	2	1½	2½	4.12	4.71
6	28.3	1½	2¼	2	2¾	3.93	4.32
8	50.3	1¾	2½	2½	3	3.83	4.12
10	78.5	1⅞	2¾	2¾	3¼	3.73	4.01
12	113.1	2	3	3	3½	3.66	3.93
15	176.7	2⅛	3¼	3¼	3¾	3.59	3.82
18	254.5	2¼	3½	3½	4	3.54	3.75
21	346	2⅜	3¾	3¾	4½	3.50	3.70
24	452	2½	4	4	5	3.47	3.67
27	573	2⅝	4¼	4¼	5½	3.45	3.64
30	707	2¾	4½	4½	6	3.43	3.62
33	855	2⅞	4¾	5	6½	3.41	3.60
36	1018	3	5	5½	7	3.40	3.58

74. Calculation of Compound Winding.—In a compound dynamo the series winding supplies the excitation necessary to produce a potential equal to that lost by armature and series field resistance and by armature reaction. Therefore, the number of shunt ampere-turns for a compound wound machine is the magnetizing force needed *on open circuit*, and the number of series ampere-turns required to maintain constant voltage is the *difference* between the excitation needed for *normal load* and that on *open circuit*. The proper number of shunt and series ampere-turns is computed as follows:

The flux, Φ_0, required on open circuit is that number of lines of force which will produce the no-load or terminal E. M. F., E_0, of the dynamo, or, by formula (**21**), page 41:

$$\Phi_0 = \frac{6 \times 10^9 \times n_p \times E_0}{N \times n_1};$$

hence, the number of shunt ampere-turns needed to overcome, *on open circuit*, the reluctances of air gaps, armature core, and magnet frame, is:

$$AT_0 = at_{g_0} + at_{a_0} + at_{m_0}, \ldots\ldots\ldots\ldots (\mathbf{52})$$

in which the magnetizing forces of the various portions of the magnetic circuit are computed with reference to the flux densities corresponding to the above no-load flux Φ_0. The compensating ampere-turns are missing from this formula, because there is no armature reaction on open circuit, as no current flows in the armature.

The armature flux at normal load is:

$$\Phi = \frac{6 \times 10^9 \times n_p \times E}{N \times n_1},$$

where E is the total E. M. F. of the dynamo at normal load.

The total ampere-turns needed for excitation at normal load, therefore, are obtained by computing AT from formula (**37**), page 79, using the flux densities corresponding to the normal flux Φ. Since AT is supplied by the combined effect of the shunt and series winding, the difference between AT and AT_o must be the number of series-ampere turns required, or

$$AT_{se} = AT - AT_o \ldots\ldots\ldots\ldots (53)$$

The total E. M. F. of an *ordinary compound dynamo* is:

$$E = E_o + 1.25 \times C \times r_a, \ldots\ldots\ldots (54)$$

where C is the current output and r_a the armature resistance of the machine, it being here assumed as an approximation that the series field resistance is $\frac{1}{4}$ of the armature resistance, which is an ample allowance.

In case the machine is to be *over-compounded* for loss in the line, the percentage of drop—usually 5 per cent.—is to be included into the output E. M. F.; hence the total E. M. F. generated at normal load, for 5 per cent. over-compounding, is

$$E = 1.05 \times E_o + 1.25 \times C \times r_a. \ldots (55)$$

After having determined the number of shunt and series ampere-turns giving the desired regulation, the calculation of the compound winding merely consists in the respective application of the methods given in Pars. **72** and **73.**

The number of turns in the series field coils is AT divided by the normal current of the machine, which is known. The large conductors needed for the series coils of compound dynamos should have a cross-section of 1,000 to 1,500 circular mils per ampere.

In calculating the number of shunt turns, the total allowable power dissipation, w_m, in the magnets must be diminished by the power dissipated in the series winding, which can be easily computed by multiplying the square of the current by the series field resistance. If the shunt dissipation so remaining is found too small to obtain a practical number of shunt turns, the size of the series wire must be increased in order to reduce the series resistance and thus to allow more power dissipation for the shunt winding.

In the calculation of a *differential winding*, the proceeding is practically the same as in a compound winding. The only difference between the two is that in a differential winding, since the series coils are wound *in opposition* to the shunt coils, AT_0 is greater than AT, hence AT_{se} becomes negative.

The calculation of magnet windings by means of formulas (**37**) to (**55**), respectively, is best understood by applying them to specific cases.

75. Data for Magnet Winding.—Table **28**, page 102, gives the areas, the usual diameter, the number of turns per inch, and the weight and resistance of insulated magnet wire. Magnet wires, except the large sizes down to No. 3, are usually insulated by a single cotton covering (S. C. C.), the large sizes being double cotton covered. This table is intended to be employed in calculating magnet windings, and its use will be seen from the following paragraphs.

76. Determination of Series Field Winding for Bipolar Smooth-Armature Machine.—To show the application of the method given in Par. **72**, let us assume that the machine represented in Fig. 25 is a 35 H. P. series motor to be supplied with 500 volts and 65 amperes. The ampere-turns required for compensating armature reaction, though in this case not exactly the same as determined in Pars. **66** and **67**, are approximately correct, because the number of turns for 500 volts must be increased in about the same proportion as the current strength in them is reduced. In taking the total number of ampere-turns as obtained above, no serious error is therefore committed.

The number of turns is obtained by dividing the total number of ampere-turns by the current, which is 65 amperes. In case of the smooth-armature design, AT was found 17,630 ampere-turns; therefore, by (**46**),

$$T = \frac{17630}{65} = \mathbf{272} \text{ turns.}$$

TABLE 28.

DATA OF BARE AND INSULATED MAGNET WIRE.

1	2	3	4	5	6	7	8
Size, B. & S.	Diam. inches. Bare Wire.	Area, Cir. Mils. Bare Wire.	Diam. of S. C. C. Wire.	Number of turns per inch. S. C. C.	Lbs. per foot, Bare Wire.	Lbs. per foot, S. C. C. Wire.	Ohms per foot at 20° C.
1	.289	83,521	.309 [1]	3.23 [1]	.2533	.259 [1]	.000124
2	.258	66,564	.278 [1]	3.59 [1]	.2009	.206 [1]	.000156
3	.229	52,441	.249 [1]	4.01 [1]	.1593	.168 [1]	.000197
4	.204	41,616	.216	4.63	.1264	.1292	.000248
5	.182	33,124	.194	5.16	.1002	.1023	.000313
6	.162	26,244	.172	5.82	.0795	.0812	.000394
7	.1443	20,832	.154	6.5	.0630	.0645	.000497
8	.1285	16,512	.139	7.2	.0500	.0512	.000627
9	.1144	13.087	.124	8.1	.0396	.0406	.000791
10	.10190	10,384	.112	8.9	.0314	.0323	.000992
11	.09074	8,234	.101	9.9	.0249	.0257	.00126
12	.08081	6,530	.088	11.4	.0198	.0203	.00159
13	.07196	5,178	.079	12.7	.0157	.0161	.00200
14	.06408	4,106	.071	14.1	.0124	.0128	.00252
15	.05707	3,257	.064	15.6	.0099	.0103	.00318
16	.05082	2,583	.058	17.3	.0078	.0081	.00401
17	.04526	2,048	.050	20.0	.0062	.0064	.00506
18	.04030	1,624	.045	22.2	.0049	.0051	.00638
19	.03589	1,288	.041	24.4	.0039	.0041	.00804
20	.03196	1,021	.037	27.0	.0031	.00325	.01014
21	.02846	810	.033	30.3	.00245	.00260	.01275
22	.02535	643	.030	33.3	.00195	.00209	.01608
23	.02257	509	.028	35.7	.00154	.00164	.02030
24	.02010	404	.025	40.0	.00122	.00133	.02560
25	.01790	320	.023	43.5	.00097	.00106	.03225
26	.01594	254	.021	47.7	.00077	.00085	.04075
27	.01420	202	.019	52.6	.00061	.00068	.05135
28	.01264	160	.017	58.8	.000484	.00054	.0648
29	.01126	127	.015	66.7	.000384	.00043	.0818
30	.01003	101	.014	71.4	.000304	.00034	.1030

[1] Double Cotton Covered.

Allowing 1,250 circular mils per ampere, the cross-section of the wire is found:

$$1{,}250 \times 65 = \mathbf{81{,}250} \text{ circular mils,}$$

which is slightly less than the sectional area of No. *1* B. & S. wire. As this size of wire would ordinarily be rather clumsy to handle, it is better to use several smaller conductors in parallel. For example, we find in Table **28**, page 102, that *three No. 6* wires have a combined sectional area of 3 × 26,244 = 78,732 circular mils, which is slightly smaller than found above and gives about 1,210 circular mils per ampere. No. 6 S.C.C. wire has a diameter of .172 inch.

Since the magnet core for the smooth-armature machine is 13½ inches long, the actual length of the winding space will be about 12½ inches, when allowing for end discs and insulation of the spool ends. The number of turns per layer is therefore 12½ ÷ .172 = 72, and, since for three wires in parallel the total number of turns is 3 × 272 = 816, or 408 on each core, there must be 408 ÷ 72 = 6 layers of No. 6 wire in each coil. The height of winding will therefore be 6 × .172 = 1⅛ inches, allowing for core insulation.

The diameter of the core being 10 inches, the average length of one turn is:

$$l_t'' = (10 + 1\tfrac{1}{8}) \times \pi = \mathit{35} \text{ inches, or } \mathit{2.92} \text{ feet.}$$

There are 408 ÷ 3 = *136* turns of each wire on each core-the length of each No. 6 wire per core, therefore, is 136 × 2.92 = *397* feet, and its resistance at 20° C., from Table **28**, is 397 × .000394 = *.156* ohm. Since there are three of these wires in parallel and two coils in series, the combined resistance of the two magnets at 20° C. is

$$(.156 \div 3) \times 2 = \mathbf{.104} \text{ ohm.}$$

The working temperature may be taken as 60° C., that is, 25° C. plus the average rise of 35° C., and since the increase in resistance is about .4 per cent. for each rise of one degree C., the resistance will become 35 × .4 = 14 per cent. greater, that is,

$$.104 \times 1.14 = \mathbf{.12} \text{ ohm.}$$

The current being 65 amperes, the drop in the field winding is $65 \times .12 = \mathit{7.8}$ volts, which is $7.8 \div 500 = .0156$, or 1.56 per cent. of the voltage supplied, being a moderate amount.

The power loss in the series field coils is

$$65^2 \times .12 = \mathit{507} \text{ watts.}$$

The cylindrical surface of each coil is:

$$(10 + 2 \times 1\tfrac{1}{8}) \times \pi \times 12\tfrac{1}{2} = 480 \text{ square inches.}$$

It is proper, also, to consider the ends of the coils as part of the cooling surface, each of them being

$$11\tfrac{1}{8} \times \pi \times 1\tfrac{1}{8} = 39 \text{ square inches.}$$

This makes a total surface of $480 + 78 = 658$ square inches for one coil, or *1,316* square inches for both. The specific cooling surface of the field winding is, therefore:

$$1{,}316 \div 507 = \mathbf{2.6} \text{ square inches per watt,}$$

which is within the practical limits. If the number of square inches per watt is found below 1½, the coil should be wound with the next larger size wire, which would decrease the power loss and increase the cooling surface, thereby augmenting the number of square inches per watt.

77. Determination of Series Winding for Bipolar Toothed-Armature Machine.—The series winding for the toothed-armature core machine will be as follows: For the toothed-armature machine $AT = 9{,}000$ ampere-turns, hence the number of turns:

$$T = \frac{9.000}{65} = \mathbf{140.}$$

The cores being 9 inches long, the available space for the winding will be about 8¼ inches. Since the diameter of No. 6 magnet wire is .172 inch, each core can therefore be wound with $8\tfrac{1}{4} \div .172 = 48$ turns of No. 6 wire. Taking again 3 strands of No. 6 wire, as in Par. **76**, the number of turns per core is $(140 \times 3) \div 2 = 210$, making the number of layers 210 ÷ 48 = 5. The corresponding winding depth is 5 × .172 = 1 inch, allowance being made for core insulation; and the mean turn, since the core diameter in this case is 10 inches, will be

$$l_t'' = (10 + 1) \times \pi = 34.56 \text{ inches, or } 2.85 \text{ feet.}$$

The total resistance of the two series coils, since there are 3 times 70 turns of No. 6 wire in parallel in each core, is:

$$r_{se} = \frac{2 \times 70 \times 2.85 \times .000394}{3} = \mathbf{.0524} \text{ ohm at } 20^\circ \text{ C.,}$$

$$\text{or} \qquad .0368 \times 1.16 = \mathbf{.061} \text{ ohm at } 60^\circ \text{ C.}$$

The power loss in the magnet coils, therefore, is

$$65^2 \times .061 = 258 \text{ watts,}$$

while the cooling surface is:

$$S_M = (10 + 2) \times \pi \times 8\tfrac{1}{4} + 2 \times 34.56 \times 1 = 380 \text{ square inches per coil, or } \mathbf{760} \text{ square inches total.}$$

This makes the specific cooling surface

$$760 \div 258 = \mathbf{2.95} \text{ square inches per watt,}$$

which, according to Par. **72**, corresponds to a tempera-rise of 30° C.

78. Determination of Shunt Winding for Bipolar Smooth-Armature Motor.—Let the given motor be the same as considered in Par. **76**. For a shunt winding, the required size of wire is obtained from formula (**49**), in which, for the case of a motor, E' is usually the total supply voltage, a field rheostat being seldom employed with the ordinary motor. Substituting in (**49**) the value AT = 17,630 ampere-turns (as determined in Par. **66**), E' = 500 volts, and $l_t'' = 10 \times 3.73 = 37.3$ inches (from Table **27**), we obtain:

$$d_m^2 = \frac{17{,}630 \times 37.3}{500} = \mathbf{1{,}310} \text{ circular mils.}$$

The nearest size wire, according to Table **28**, is No. *19* B. & S., which has a diameter of .041 when insulated for use as magnet wire.

The approximate winding depth for a bipolar 10-inch core is found in Table **27** to be $1\frac{7}{8}$ inches; the length of the coil space on each core is $12\frac{1}{2}$ inches; hence, the total cooling surface of the two coils:

$$S_M = (10 + 2 \times 1\tfrac{7}{8}) \times \pi \times 12\tfrac{1}{2} \times 2 + 37.3 \times 1\tfrac{7}{8} \times 4 = \mathit{1{,}360} \text{ square inches.}$$

For a rise of 30° C., which we will assume to be prescribed in this case, we find by (**51**):

$$C_{sh} = \frac{30 \times 1{,}360}{75 \times 500} = \mathit{1.09} \text{ amperes.}$$

Dividing this into the number of ampere-turns, the required number of turns is obtained:

$$T = \frac{17{,}630}{1.09} = \mathit{16{,}200} \text{ turns, total, or } \mathit{8{,}100} \text{ turns per core.}$$

The number of wires that can be placed in one layer is $12\frac{1}{2} \div .041 = 300$; hence, the number of layers needed is $8{,}100 \div 300 = \mathit{27}$. The actual height occupied by these 27 layers will be

$$27 \times .041 = 1.1 \text{ inches,}$$

making a winding depth of about $1\frac{1}{4}$ inches, which is considerably less than the height assumed above by the aid of Table **27**. Since for this height the cooling surface would be appreciably smaller than obtained above, the shunt current would have to be correspondingly smaller, which in turn would increase the number of turns, making the winding depth larger. Taking, therefore, a value between the two, or, say, $1\frac{1}{2}$ inches, the cooling surface becomes:

$$S_M = (10 + 2 \times 1\tfrac{1}{2}) \times \pi \times 12\tfrac{1}{2} \times 2 + 11\tfrac{1}{2} \times \pi \times 1\tfrac{1}{2} \times 4 = \mathit{1{,}237} \text{ square inches,}$$

and we have:

$$\text{Shunt current:} \quad C_{sh} = \frac{30 \times 1{,}237}{75 \times 500} = \mathbf{.99} \text{ ampere;}$$

$$\text{Number of turns:} \quad T = \frac{17{,}630}{.99} = \mathbf{17{,}800};$$

Number of layers: $\frac{17.800}{2 \times 300} = \mathbf{30}.$

The height occupied by these 30 layers is

$$30 \times .041 = 1.24 \text{ inches,}$$

which gives a winding depth of about 1½ inches, as taken above.

There being 30 layers of 300 turns each, or 9,000 turns in all, in each coil, the total length of wire in both coils is:

$$2 \times 9{,}000 \times \frac{11\frac{1}{2} \times \pi}{12} = 54{,}200 \text{ feet;}$$

hence, the shunt resistance at 20° C., according to Table **28**:

$$r_{sh} = 54{,}200 \times .00804 = \mathbf{436} \text{ ohms,}$$

which at 55° C. (25° + 30°) amounts to

$$r_{sh}' = 436 \times 1.14 = \mathbf{498} \text{ ohms.}$$

The actual shunt current is, therefore:

$$C_{sh} = \frac{500}{498} = \mathbf{1} \text{ ampere,}$$

which multiplied by the number of turns gives the actual excitation:

$$AT = 2 \times 9{,}000 \times 1 = \mathbf{18{,}000} \text{ ampere-turns.}$$

This is about 2 per cent. in excess of the magnetizing force needed.

The total weight of the insulated wire in both coils is, by Table **28**:

$$wt_m = 54{,}200 \times .0041 = \mathbf{222} \text{ pounds,}$$

or **111** pounds on each magnet.

Though not excessive, this is a somewhat greater weight of wire than would ordinarily be used on a machine of this kind. This is due to the fact that the length of the armature is rather small for a bipolar machine, but was so chosen in order to adopt the same armature for the 4-pole design as well. By increasing the length of the armature, the same length of conductor will occupy less height, thereby reducing the gap space and correspondingly diminishing the number of ampere-turns required.

79. Determination of Shunt Winding for Four-Pole Toothed-Armature Generator.—Inserting into (**49**) the value of the ampere-turns found in Par. **69** for the machine shown in Fig. 26, which in this case we will assume to be a 125-volt generator, we obtain

$$d_m^2 = \frac{7{,}050 \times 28.6}{\frac{1}{2}(125 - 25)} = \mathbf{4{,}030} \text{ circular mils.}$$

Herein 28.6 is the approximate mean length of one turn on a 6⅝-inch core for a multipolar machine, found from Table **27**, as shown on page 98. The factor ½ in the denominator indicates that in the present case the four magnets are to be connected in series (see Par. **73**). The deduction of 25 volts represents an allowance of 20 per cent. for regulating resistance.

The above value of d_m^2 is almost exactly the area of No. **14** B. & S. wire having a diameter of .071 inch when insulated (see Table **28**).

Using the value 2¼″ given in Table **27** for the average winding depth of a 6-inch multipolar magnet, and taking 3¼ inches as the available length of each winding space, the cooling surface is found:

$$S_m = (6\tfrac{5}{8} + 2 \times 2\tfrac{1}{4}) \times \pi \times 3\tfrac{1}{4} \times 2 + 28.6 \times 2\tfrac{1}{4} \times 2$$
$$= \mathit{355} \text{ square inches.}$$

In this case. only one end surface of each coil is considered as cooling surface, because in a multipolar frame the polepieces cover up the inner ends. For a rise of 30° C., the shunt current is therefore obtained by (**51**), thus:

$$C_{sh} = \frac{30 \times 355}{75 \times 50} = \mathit{2.84} \text{ amperes,}$$

giving a specific cooling surface of

$$\frac{355}{50 \times 2.84} = \mathbf{2.5} \text{ square inches per watt.}$$

The number of turns required with the above shunt current is:

$$T = \frac{7{,}050}{2.84} = \mathbf{2{,}480}, \text{ or } \mathbf{1{,}240} \text{ turns per core.}$$

The total number of ampere-turns as found from formulas **(37)**, **(42)**, **(43)**, and **(45)** must in a multipolar ring machine be supplied to *each two cores*, as the various pairs of cores form a number of parallel magnetic circuits. In order to obtain a total number of AT ampere-turns, each of these parallel circuits must therefore be wound with AT ampere-turns.

Since the number of turns per layer is

$$3\tfrac{1}{4} \div .071 = \mathit{45},$$

there must be

$$1{,}240 \div 45 = \mathit{28} \text{ layers,}$$

making a winding depth of

$$28 \times .071 = \mathit{2} \text{ inches,}$$

not including the core-insulation, or about $\mathit{2}\tfrac{1}{8}$ inches total.

The resistance of the four magnet coils in series is:

$$r_{\text{sh}} = 4 \times 45 \times 28 \times \frac{(6\tfrac{5}{8} + 2\tfrac{1}{8}) \times \pi}{12} \times .00252$$

$$= \mathbf{29} \text{ ohms at } 20^\circ \text{ C.,}$$

or

$$29 \times 1.14 = \mathbf{33} \text{ ohms at } 55^\circ \text{ C.}$$

The actual shunt current required to produce the desired number of ampere-turns is:

$$C_{\text{sh}} = \frac{7{,}050}{2 \times 45 \times 28} = \mathbf{2.8} \text{ amperes;}$$

hence, the total resistance of the shunt circuit:

$$\frac{125}{2.8} = \mathbf{44.7} \text{ ohms,}$$

which makes the resistance of the regulating rheostat

$$44.7 - 33 = \mathbf{11.7} \text{ ohms.}$$

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The weight of the magnet winding is:

$$wt_m = 45 \times 28 \times \frac{8\frac{3}{4} \times \pi}{12} \times .0128 = \mathbf{37} \text{ lbs. per core,}$$

or $$37 \times 4 = \mathbf{148} \text{ pounds, total.}$$

80. Determination of Compound Winding for Four-Pole Toothed-Armature Generator.—The machine considered in the preceding paragraph is to be compound wound for 5 per cent. over compounding; the temperature increase to be 35° C. The four series coils are to be connected in parallel, and the four shunt coils in two groups of two coils each.

We must first determine the respective numbers of shunt and series ampere turns. We assume the number of armature turns to be 250, and 125 to be the voltage on open circuit. Proceeding as indicated in Par. **74**, we then obtain the flux required on open circuit:

$$\Phi_o = \frac{6 \times 10^9 \times 2 \times 125}{250 \times 1,200} = \mathbf{5,000,000} \text{ lines,}$$

which is the number upon which the calculations in the previous paragraphs are based. The flux densities on open circuit are, therefore, the same as in Par. **69**, and in this case we have:

For air-gaps: $\mathbf{B}_{g_o}'' = 45,000$; $\mathbf{H}_{g_o}'' = .313 \times 45,000$

" armature teeth: $\mathbf{B}_{a_o}' = 120,000$; $\mathbf{H}_{a_o}' = 700$

" armature core: $\mathbf{B}_{a_o}'' = 80,000$; $\mathbf{H}_{a_o}'' = 31$

" magnet frame: $\mathbf{B}_{m}'' = 90,000$; $\mathbf{H}_{m_o}'' = 51$.

Hence, the excitation on open circuit, or the *shunt excitation:*

$at_{g_o} = .313 \times 45,000 \times \frac{1}{4} = 3,520$ ampere-turns;

$at_{a_o}' = 700 \times 2 = 1,400$ "

$at_{a_o}'' = 31 \times 5 = 170$ "

$at_{m_o} = 51 \times 26 = 1,330$ "

Total: $AT = \mathbf{6,420}$ "

The total E. M. F. at normal load, according to formula (**55**), if we assume the armature resistance to be .0125 ohm, is:

$$E = 1.05 \times 125 + 1.25 \times 240 \times .0125 = \mathit{135} \text{ volts.}$$

Inserting this value instead of the no-load voltage into (**21**), the flux required for excitation at normal load is found:

$$\Phi = 5{,}000{,}000 \times \frac{135}{125} = \mathbf{5{,}400{,}000} \text{ lines.}$$

The flux densities and specific magnetizing forces for normal load, consequently, are:

$$\mathbf{B}_g'' = 45{,}000 \times \frac{135}{125} = 48{,}600; \quad \mathbf{H}_g'' = .313 \times 48{,}600;$$

$$\mathbf{B}_a = 120{,}000 \times \frac{135}{125} = 130{,}000; \quad \mathbf{H}_a' = 1{,}100;$$

$$\mathbf{B}_a'' = 80{,}000 \times \frac{135}{125} = 86{,}400; \quad \mathbf{H}_a'' = 43;$$

$$\mathbf{B}_m'' = 90{,}000 \times \frac{135}{125} = 97{,}200; \quad \mathbf{H}_m'' = 78;$$

and the magnetizing forces at normal load are obtained as follows:

$$\begin{array}{lll}
at_g = .313 \times 48{,}600 \times \frac{1}{4} & = 3{,}800 & \text{ampere-turns.} \\
at_a = 1100 \times 2 & = 2{,}200 & \text{"} \\
at_a'' = 43 \times 5 & = 240 & \text{"} \\
at_m = 78 \times 26 & = 2{,}030 & \text{"} \\
at_r \text{ (from Par. } \mathbf{69}) & = 630 & \text{"} \\
\hline
\text{Total:} \qquad AT & = \mathbf{8{,}900} & \text{"}
\end{array}$$

As shown in Par. **74**, the series winding must supply the difference between the ampere-turns on normal load and on open circuit, or, by (**53**):

$$AT_{se} = 8{,}900 - 6{,}420 = \mathbf{2{,}480} \text{ ampere-turns.}$$

The series winding is, therefore, calculated as follows:

The four series coils being connected in parallel, the current in each coil is

$$240 \div 4 = 60 \text{ amperes,}$$

while the magnetizing force per magnet is

$$2{,}480 \div 2 = 1{,}240 \text{ ampere-turns;}$$

hence, the number of series turns per coil:

$$T_{se} = \frac{1240}{60} = \mathbf{21.}$$

The size of the series field conductor is:

$$d_m^2 = 60 \times 1{,}000 = \mathbf{60{,}000} \text{ circular mils,}$$
$$\text{or } \mathbf{3} \textit{ No. } \mathbf{7} \text{ wires.}$$

The series winding is usually wound upon the core first. Assuming it to occupy a height of ½ inch, the mean length of one turn is:

$$l_t'' = (6\tfrac{5}{8} + \tfrac{1}{2}) \times \pi = 22.4 \text{ inches, or } 1.87 \text{ feet.}$$

There being on each magnet 3 coils in parallel, each having 21 turns, the joint series resistance (four magnets in parallel) is therefore found:

$$r_{se} = \frac{21 \times 1.87 \times .000497}{3 \times 4} = \mathbf{.00163} \text{ ohm at } 20^\circ \text{ C.,}$$

or

$$.00163 \times 1.12 = \mathbf{.00183} \text{ ohm at } 50^\circ \text{ C.}$$

Hence, the total power loss in the series winding:

$$240^2 \times .00183 = \mathbf{105} \text{ watts.}$$

Since the diameter of No. 7 wire is .154 inch, each layer will hold

$$(4 - \tfrac{1}{2}) \div .154 = \mathbf{21} \text{ turns,}$$

and there will be

$$(21 \times 3) \div 21 = \mathbf{3} \text{ layers,}$$

occupying a height of

$$3 \times .154 = \tfrac{1}{2} \text{ inch.}$$

This, according to Table **27**, leaves a winding depth of about $1\frac{3}{4}$ inches for the shunt coil which is wound over the series coil. The total weight of the series winding is:

$$wt_{se} = 21 \times 3 \times 4 \times 1.87 \times .0645 = \mathbf{30.5} \text{ pounds.}$$

The size of the shunt wire is:

$$d_m^2 = \frac{6.420 \times 28.6}{125 - 15} = \mathbf{1{,}670} \text{ circular mils, or No. } \mathbf{18} \text{ wire.}$$

In Par. **79**, the total cooling surface of two magnets of this machine is found 355 square inches; the power loss in the series winding is $\frac{1}{2} \times 105 = 52$ watts per magnetic circuit; hence, the shunt current:

$$C_{sh} = \frac{(\frac{35}{75} \times 355) - 52}{110} = \mathbf{1.04} \text{ amperes.}$$

Number of shunt turns:

$$T_{sh} = \frac{6.420}{1.04} = \mathbf{6{,}170} \text{ per circuit, or } \mathbf{3{,}085} \text{ turns per core.}$$

The diameter of No. 18 wire is .045 inch; hence, there are

$$3\tfrac{1}{2} \div .045 = \mathbf{77} \text{ turns}$$

in each layer, and the number of layers becomes

$$3{,}085 \div 77 = \mathbf{40},$$

for which the winding depth is

$$40 \times .045 = 2 \text{ inches.}$$

The mean length of the shunt turn, therefore, is:

$$l_t'' = (6\tfrac{5}{8} + 2 \times \tfrac{1}{2} + 2) \times \pi = 30.24 \text{ inches, or } 2.54 \text{ feet.}$$

Resistance of shunt winding:

$$r_{sh} = 77 \times 40 \times 2.54 \times .00638 = \mathbf{50} \text{ ohms, at } 20^\circ \text{ C.,}$$

or

$$r_{sh}' = 50 \times 1.12 = \mathbf{56} \text{ ohms, at } 50^\circ \text{ C.}$$

Actual shunt current:

$$C_{sh} = \frac{6.420}{2 \times 77 \times 40} = \mathbf{1.04} \text{ amperes.}$$

Total resistance of shunt circuit:

$$r = \frac{125}{2 \times 1.04} = \mathbf{60} \text{ ohms.}$$

Resistance of field regulator:

$$60 - 56 = \mathbf{4} \text{ ohms.}$$

Weight of shunt winding:

$$wt_{sh} = 4 \times 77 \times 40 \times 2.54 \times .0051 = \mathbf{159.5} \text{ lbs.}$$

Total weight of winding:

$$wt_m = 159\tfrac{1}{2} + 30\tfrac{1}{2} = \mathbf{190} \text{ lbs.}$$

CALCULATION OF EFFICIENCIES.

81. Electrical Efficiency.—The *electrical efficiency*, or. as it is sometimes called, the *economic coefficient* of a dynamo, is the ratio of its useful power to the total electrical power in its armature. The total electrical power is the sum of the useful power and of the power losses due to the armature and field resistances; hence the electrical efficiency of a *generator:*

$$El.\ Eff. = \frac{W}{W'} = \frac{W}{W + w_a + w_m}, \ldots\ldots\ldots\ldots (56)$$

and that of a *motor:*

$$El.\ Eff. = \frac{W'}{W} = \frac{W - (w_a + w_m)}{W}, \ldots\ldots\ldots\ldots (57)$$

where W = electrical power at terminals of machine;
W' = electrical power active in armature;
w_a = power absorbed by armature winding;
w_m = power used for field excitation.

In the case of a *generator*, W is the *output* available at the brushes, while in a *motor* it is the total power delivered to the terminals, that is, the *intake* of the motor.

82. Formulas for Electrical Efficiency.—Inserting into (**56**) and (**57**) the expressions for W, w_a, and w_m in terms of E. M. F., current strength, and resistance, the following formulas for the electrical efficiency are obtained:

Series-wound generator:

$$El.\ Eff. = \frac{EC}{EC + C^2\,(r_a' + r_{se}')};\ldots\ldots\ldots\ldots(\mathbf{58})$$

Shunt-wound generator:

$$El.\ Eff. = \frac{EC}{EC + C_a^2 r_a + C_{sh}^2 r_{sh}''};\ldots\ldots\ldots\ldots(\mathbf{59})$$

Compound-wound generator:

$$El.\ Eff. = \frac{EC}{EC + C_a^2\,(r_a' + r_{se}') + C_{sh}^2 r_{sh}''};\ldots(\mathbf{60})$$

Series-wound motor:

$$El.\ Eff. = \frac{EC - C^2\,(r_a' + r_{se}')}{EC};\ldots\ldots\ldots\ldots(\mathbf{61})$$

Shunt wound motor:

$$El.\ Eff. = \frac{EC - (C_a^2 r_a' + C_{sh}^2 r_{sh}'')}{EC};\ldots\ldots\ldots\ldots(\mathbf{62})$$

Compound-wound motor:

$$El.\ Eff. = \frac{EC - [C_a^2\,(r_a' + r_{se}') + C_{sh}^2 r_{sh}'']}{EC}\ldots(\mathbf{63})$$

The symbols used in the above formulas (**58**) to (**63**) represent E. M. F., current strengths, and resistances, as follows:

E = terminal voltage of generator, or supply voltage of motor;

C = current output of generator at brushes, or current intake of motor at brushes;

C_{sh} = current flowing in shunt circuit;

C_a = armature current; for a *generator*, $C_a = C + C_{sh}$; for a *motor*, $C_a = C - C_{sh}$;

r_a' = armature resistance, warm;
r_{se}' = series field resistance, warm;
r_{sh}'' = resistance of shunt circuit, including field regulator.

The electrical efficiency of modern dynamos is very high, ranging from *.8*, or *80* per cent., for small machines, to as high as *.995*, or *99½* per cent., for very large generators. Since the electrical efficiency does not include waste by hysteresis, eddy currents, and friction, but is dependent upon the power losses due to heating by the current only, it may be adjusted to any desired value by properly proportioning the resistances of the machine.

83. Examples of Calculating Electrical Efficiency.—The following examples show the application of formulas **(58)** to **(63)**:

(1) *What is the electrical efficiency of a series-wound generator, producing* **2,500** *volts and* **10** *amperes, if its warm armature resistance is* **9** *ohms and its magnet resistance is* **11** *ohms?*

Solution.—By formula **(58)** we have in this case:

$$El.\ Eff. = \frac{2500 \times 10}{(2500 \times 10) + [10^2 \times (9 + 11)]} = \frac{25{,}000}{25{,}000 + 2000}$$
$$= \frac{25{,}000}{27{,}000} = \mathbf{.925}, \text{ or } \mathbf{92\tfrac{1}{2}\%}.$$

(2) *Find the electrical efficiency of a shunt-wound* **3** *K. W.* **125**-*volt generator, knowing its armature resistance (warm) to be* **.32** *ohm, and its shunt resistance, including field regulator,* **125** *ohms.*

Solution.—The current output of this machine is $\frac{3000}{125}$ = *24* amperes, and the shunt current is found, by Ohm's Law, $\frac{125}{125}$ = *1* ampere. Hence the total current flowing in the armature, being the sum of current output and shunt current, is 24 + 1 = *25* amperes. By **(59)** we therefore obtain:

$$El.\ Eff. = \frac{3000}{3000+(25^2\times.32)+(1^2\times125)} = \frac{3000}{3000+200+125}$$
$$= \frac{3000}{3325} = \mathbf{.902},\text{ or } \mathbf{90.2\%}.$$

(3) *A compound-wound* **50** *K. W. generator gives a terminal E. M. F. of* **500** *volts. Its armature resistance (warm) is* **.12** *ohm; its series field resistance is* **.04** *ohm; and its shunt resistance is* **270** *ohms. Compute its electrical efficiency.*

Solution.—The current output is $\frac{50,000}{500} = 100$ amperes; the shunt current is $\frac{500}{270} = 1.85$ amperes. Hence by **(60)**:

$$El.\ Eff. = \frac{50,000}{50,000+[101.85^2\times(.12+.04)]+(1.85^2\times270)}$$
$$= \frac{50,000}{50,000+1660+925} = \frac{50,000}{52,585} = \mathbf{.95},\text{ or } \mathbf{95\%}.$$

(4) *Find the electrical efficiency of a series motor which takes a current of* **100** *amperes when supplied at* **220** *volts, if its armature has a resistance of* **.11** *ohm, and its field a resistance of* **.015** *ohm.*

Solution.—By **(61)**:

$$El.\ Eff. = \frac{(220\times100)-[100^2\times(.11+.015)]}{220\times100} = \frac{22,000-1250}{22,000}$$
$$= \frac{20,750}{22,000} = \mathbf{.9425},\text{ or } \mathbf{94\tfrac{1}{4}\%}.$$

(5) *What is the electrical efficiency of the machine considered under* **(2)**, *if it is run as a motor from a* **125**-*volt circuit, being supplied with* **26** *amperes?*

Solution.—By **(62)**:

$$El.\ Eff. = \frac{(125\times26)-[(25^2\times.32)+(1^2\times125)]}{125\times26} = \frac{3250-325}{3250}$$
$$= \frac{2925}{3250} = \mathbf{.90},\text{ or } \mathbf{90\%}.$$

(6) *A certain* **75** *H. P. compound-wound motor takes* **140** *amperes on a* **440**-*volt circuit; its armature resistance is* **.06** *ohm; series field resistance,* **.007** *ohm; shunt resistance,* **293** *ohms; compute its electrical efficiency.*

Solution.—The current employed for shunt excitation in this case is $\frac{440}{293} = 1.5$ amperes; hence the current flowing in the armature, $140 - 1.5 = 138.5$ amperes, and therefore by formula (**63**):

$$El.\ Eff. = \frac{(440 \times 140) - [(138.5^2 \times .067) + (1.5^2 \times 293)]}{440 \times 140}$$

$$= \frac{61{,}610 - 1945}{61{,}610} = \frac{59{,}665}{61{,}610} = \mathbf{.968}, \text{ or } \mathbf{96.8\%}.$$

84. Commercial Efficiency.—By the *commercial efficiency*, or *net efficiency*, of a dynamo-electric machine is meant the ratio of its output to its intake. The *intake of a generator* is the mechanical power required to drive it, and is the sum of the total electrical power generated in the armature and of the power losses due to hysteresis, eddy currents, and friction; the *intake of a motor* is the electrical power delivered to its terminals. The *output of a generator* is the electrical power available at its terminals; the *output of a motor* is the mechanical power available at its shaft, and consists in the useful power of the armature diminished by the losses due to hysteresis, eddy currents, and friction.

The commercial efficiency of a *generator*, therefore, is:

$$Com.\ Eff. = \frac{W}{W''} = \frac{W}{W' + w_o} = \frac{W}{W' + w_h + w_e + w_f}$$

$$= \frac{W}{W + w_a + w_m + w_h + w_e + w_f}, \ldots\ldots \textbf{(64)}$$

and that of *motor:*

$$Com.\ Eff. = \frac{W''}{W} = \frac{W' - w_o}{W} = \frac{W - (w_h + w_e + w_f)}{W}$$

$$= \frac{W - (w_a + w_m + w_h + w_e + w_f)}{W}; \ldots (\mathbf{65})$$

in which W = electrical power at terminals; that is, output of generator, or intake of motor;

W' = electrical power active in armature;

W'' = mechanical power at dynamo shaft; that is, driving power of generator, or mechanical output of motor, respectively;

w_a = power absorbed by armature winding;

w_m = power used for field excitation;

w_h = power consumed by hysteresis;

w_e = power consumed by eddy currents;

w_f = power loss due to air resistance, brush friction, journal friction, etc.;

w_o = power required to run machine at normal speed on open circuit;

$w_o = w_h + w_e + w_f$.

85. Formulas for Commercial Efficiency.—Substituting in the above formulas (**64**) and (**65**) the values of W, w_a, and w_m, the following formulas are obtained, in which the symbols employed have the same meaning as in formulas (**58**) to (**63**):

Series-wound generator:

$$Com.\ Eff. = \frac{E}{EC + C^2\,(r_a' + r_{se}') + w_h + w_e + w_f}; \ldots\ldots\ldots (\mathbf{66})$$

Shunt-wound generator:

$$Com.\ Eff. = \frac{EC}{EC + C_a^2 r_a' + C_{sh}^2 r_{sh}'' + w_h + w_e + w_f}; \ldots (\mathbf{67})$$

Compound-wound generator:

$$Com.\ Eff. = \frac{EC}{EC + C_a^2(r_a' + r_{se}') + C_{sh}^2 r_{sh}'' + w_h + w_e + w_f}; \ldots (\mathbf{68})$$

Series-wound motor:

$$Com.\ Eff. = \frac{EC - [C^2(r_a' + r_{se}') + w_h + w_e + w_f]}{EC};\ldots\ldots\textbf{(69)}$$

Shunt-wound motor:

$$Com.\ Eff. = \frac{EC - (C_a^2 r_a' + C_{sh}^2 r_{sh}'' + w_h + w_e + w_f)}{EC};\ldots\textbf{(70)}$$

Compound-wound motor:

$$Com.\ Eff. = \frac{EC - [C_a^2(r_a' + r_{se}') + C_{sh}^2 r_{sh}'' + w_h + w_e + w_f]}{EC}..\textbf{(71)}$$

86. Friction Losses in Dynamo-Electric Machines.—In the above formulas all the quantities are known from the previous calculation of the machine, except the amount of power lost by friction; the latter will not be accurately known until the machine is actually built, and must, therefore, here be assumed. Average values of w_f for various sizes of machines, as gathered from experience, are given in Table **29.**

TABLE 29.

AVERAGE FRICTION LOSSES IN DYNAMO-ELECTRIC MACHINES.

Capacity of Dynamo, in Kilowatts.	Average Friction Loss in Watts. w_f	Friction Loss in per cent. of Output.
.1	20	20%
.25	40	16
.5	60	12
1.	100	10
5.	400	8
10.	700	7
25.	1500	6
50.	2500	5
100.	4000	4
500.	17500	3½
1000.	30000	3
5000.	125000	2½

To obtain the approximate power lost by friction for any intermediate size not given in Table **29**, take the nearest, or the proportionate, percentage from the last column, and multiply the number so obtained by *10* times the output of the machine in kilowatts. The result will be the required power loss, in watts. Thus, for a *15* K. W. machine, the percentage of power loss by friction is about *6⅔* per cent.; hence the approximate amount of the power loss:

$$6\tfrac{2}{3} \times 15 \times 10 = 1000 \text{ watts.}$$

If the *nearest* percentage given in the table is taken, the power loss for a 15 K. W. machine is found

$$7 \times 15 \times 10 = 1050 \text{ watts.}$$

87. Examples of Calculating Commercial Efficiency.—To show the use of formulas (**66**) to (**71**), and of Table **29**, let us determine the *commercial efficiencies* of the machines considered in Par. **83**.

(**1**) *The* **2500**-*volt* **10**-*ampere series generator referred to in Example* (**1**) *of Par.* **83** *has a hysteresis loss of* **400** *watts, and an eddy current loss of* **100** *watts; determine its commercial efficiency.*

Solution.—According to Table **29**, the friction loss of a 25 K. W. machine is about *1500* watts; therefore, by formula (**66**):

$$\textit{Com. Eff.} = \frac{25{,}000}{25{,}000 + 2000 + 400 + 100 + 1500}$$
$$= \frac{25{,}000}{29{,}000} = \mathbf{.8625}, \text{ or } \mathbf{86\tfrac{1}{4}\%}.$$

(**2**) *Find the commercial efficiency of the* **3** *K. W. shunt-wound generator of Example* (**2**), *Par.* **83**, *if its hysteresis loss is* **25** *watts and its eddy current loss* **10** *watts.*

Solution.—From Table **29** it is found that the percentage of friction loss for a 3 K. W. machine is about 9%, hence the approximate friction loss is obtained as $9 \times 3 \times 10 =$ *270* watts. Formula (**67**), therefore, gives:

$$Com.\ Eff. = \frac{3000}{3000+200+125+25+10+270} = \frac{3000}{3630}$$
$$= \mathbf{.826}, \text{ or } \mathbf{82.6\%}.$$

(**3**) *The hysteresis loss of the* **50** *K. W. compound-wound generator given in Example* (**3**), *Par.* **83,** *is* **350** *watts, its eddy current loss* **65** *watts; what is its commercial efficiency?*

Solution.—Table **29** gives $w_f = 2500$ watts; by means of formula (**68**) we therefore obtain:

$$Com.\ Eff. = \frac{50{,}000}{50{,}000 + 1660 + 925 + 350 + 65 + 2500}$$
$$= \frac{50{,}000}{55{,}500} = \mathbf{.90}, \text{ or } \mathbf{90\%}.$$

(**4**) *What is the commercial efficiency of the* **220**-*volt series motor of Example* (**4**), *Par.* **83**, *its power loss by hysteresis being* **200** *watts, and its eddy current loss* **50** *watts?*

Solution.—The current taken by this motor is given as 100 amperes, hence its capacity is $220 \times 100 = 22{,}000$ watts, or 22 K. W., for which Table **29** gives a friction loss of approximately *6%*. Therefore, $w_f = 6 \times 22 \times 10 =$ *1320* watts, and by (**69**):

$$Com.\ Eff. = \frac{22{,}000 - (1250 + 200 + 50 + 1320)}{22{,}000}$$
$$= \frac{19{,}180}{22{,}000} = \mathbf{.872}, \text{ or } \mathbf{87.2\%}.$$

(**5**) *Determine the commercial efficiency of the shunt-wound motor given in Examples* (**2**) *and* (**5**) *of Par.* **83**, *if its iron losses are the same as given above for the* **3** *K. W. generator.*

Solution.—By (**70**):

$$Com.\ Eff. = \frac{3250 - (325 + 35 + 270)}{3250} = \frac{2620}{3250}$$
$$= \mathbf{.806}, \text{ or } \mathbf{80.6\%}.$$

(6) *What is the commercial efficiency of the* **75** *H.P. compound motor considered in Example* (**6**) *of Par.* **83**, *if its hysteresis and eddy current losses aggregate* **1200** *watts?*

Solution.—The capacity of this motor is about *60* K. W., hence the friction loss, by Table **29**, is about $w_f = 5 \times 60 \times 10 =$ *3000* watts, and by (**71**):

$$Com.\ Eff. = \frac{61{,}610 - (1945 + 1200 + 3000)}{61{,}610} = \frac{55\ 465}{61{,}610}$$

$$= \mathbf{.90}, \text{ or } \mathbf{90\%}.$$

88. Magnitude of Commercial Efficiency.—The commercial efficiency of well-designed machines ranges from .*7*, or *70* per cent., for small dynamos, to .*96*, or *96* per cent., for large ones. The commercial efficiency of a dynamo is always smaller than its electrical efficiency, since the former, besides the electrical power dissipation, includes all mechanical and magnetic power losses, such as are due to journal friction, to hysteresis, to eddy currents, and to magnetic leakage. The commercial efficiency, therefore, depends upon the amount of the electrical efficiency, upon the shape of the armature, upon the design, workmanship, and alignment of the bearings, upon the pressure of the brushes, upon the quality of the iron employed in armature and field magnets, and upon the degree of lamination of the armature core; while the electrical efficiency is a function of the electrical resistances only. The mechanical and magnetic losses vary very nearly proportionally to the speed; the no load power consumption for any given speed, consequently, is approximately equal to the open-circuit loss at normal speed multiplied by the ratio of the given to the normal speed.

89. Efficiency of Belt-Driven Machines.—In the case of *belt-driving*, the mechanical power at the dynamo shaft, in foot-pounds per second, can also be expressed by the product of the belt-speed, in feet per second, and of the effective driving power of the belt, in pounds; or, converted into watts:

$$W'' = \frac{746}{550} \times \frac{v_b'}{60} \times (F_b - f_b) = 1.3564 \times v_b'' \times (F_b - f_b), \ldots\ldots(72)$$

where 746 = number of watts equal to 1 horse-power;
550 = number of foot-pounds per second equal to 1 horse-power;
v_b' = belt velocity, in feet per minute;
v_b'' = belt velocity, in feet per second;
F_b = tension on tight side of belt, in pounds;
f_b = tension on slack side of belt, in pounds.

The commercial efficiency of a *generator*, therefore, may be expressed by:

$$Com.\ Eff. = \frac{W}{W''} = \frac{EC}{1.3564 \times v_b'' \times (F_b - f_b)}, \ldots(73)$$

and the commercial efficiency of a *motor*, by:

$$Com.\ Eff. = \frac{W''}{W} = \frac{1.3564 \times v_b'' \times (F_b - f_b)}{EC} \ldots(74)$$

90. Example of Belt-Driven Machine.—*Compute the commercial efficiency of a* **3** *K. W. belt-driven machine, if its speed is* **1800** *revolutions per minute, its pulley diameter* **6½** *inches, and if the tension on the tight side of its belt is found to be* **82** *pounds and that on the slack side* **30** *pounds.*

Solution.—The belt velocity in this case is $\frac{6\frac{1}{2} \times \pi}{12} \times 1800$ = *3060* feet per minute, or *51* feet per second. Consequently, by (**73**):

$$Com.\ Eff. = \frac{3000}{1.3564 \times 51 \times (82 - 30)} = \frac{3000}{3600}$$
$$= \mathbf{.833}, \text{ or } \mathbf{83.3\%}.$$

91. Losses in Dynamo Belting.—Since in a direct-driven generator the commercial efficiency is the ratio of the mechanical power available at the engine shaft to the electrical energy at the machine terminals, for comparisons between direct and belt-driven dynamos, the loss in belting should also be included in the formula for the commercial efficiency of the belt-driven generator. The following Table **30** contains averages of these losses for various arrangements of belts:

TABLE 30.

LOSSES IN DYNAMO BELTING.

Arrangement of Belts.	Loss in Belting in per cent. of Power Transmitted.
Horizontal Belt....................	5 to 10 per cent.
Vertical Belt......................	6 " 12 "
Countershaft and Horizontal Belt..	10 " 15 "
Countershaft and Vertical Belt....	12 " 20 "
Main and Countershaft with Belts..	20 " 30 "

92. Gross Efficiency.—The *gross efficiency,* or the *efficiency of conversion*, in a *generator* is the ratio between the total electrical power generated and the gross mechanical power delivered to the shaft; and in a *motor* it is the ratio of the mechanical output to the total electrical power in the armature.

The gross efficiency is, therefore, the quotient of the commercial and electrical efficiencies, or

$$Gr.\ Eff. = \frac{Com.\ Eff.}{El.\ Eff};\ \ldots\ldots\ldots\ldots\ldots\ldots \quad (75)$$

and consequently varies between $\frac{.7}{.85} = .825$, or $82\frac{1}{2}$ per cent., for small dynamos, and $\frac{.95}{.996} = .965$, or $96\frac{1}{2}$ per cent., for large machines.

93. Example of Gross Efficiency.—*Find the gross efficiency of the* **50** *K. W. compound-wound generator of Example* (**3**), *Pars.* **83** *and* **87**.

Solution.—The electrical efficiency of this generator was found to be *.95*, and its commercial efficiency *.872*; therefore by (**75**):

$$Gr.\ Eff. = \frac{.872}{.95} = \mathbf{.917}, \text{ or } \mathbf{91.7\%}.$$

94. Weight-Efficiency.—The *weight-efficiency* of a dynamo, that is, the output per unit weight, is obtained by dividing the output, in watts, by the weight, in pounds. The numerical value of this ratio shows at a glance whether or not the machine is designed economically, since the weight efficiency indicates how the cost of the prospective machine is going to compare with that of existing dynamos.

The weight-efficiency of modern machines ranges between *2* and *20* watts per pound, according to their speed and size. For *low-speed* dynamos, the limits are from *2* to *10* watts per pound, the former figure referring to very small machines (less than ½ K. W. capacity), and the latter to very large ones (2,000 K. W. and over). In *medium-speed* machines the weight-efficiency varies from *3* to *15* watts per pound, according to the size; and high-speed dynamos have weight-efficiencies from *5* to *20* watts per pound.

To determine the total weight of the machine, compute the weights of the magnet frame, armature, and windings from the dimensions; estimate the weights of the shaft, the bearings, and the bedplate or supporting brackets; and, according to the size and current output of the machine, allow from *5* to *25* per cent. of the total weight so found, for accessory parts, such as commutator, pulley, brushes, brush-rocker, switches, connectors, cables, etc. A small allowance for accessory parts, from *5* to *10* per cent., is to be made in the case of large machines of high voltage in which all the current-carrying parts are comparatively small; and a large allowance, from *15* to *25* per cent., in the case of small, low-voltage machines having comparatively massive current-conveying parts.

The weight of the shaft, bearings, and bed (or supporting brackets) depends upon the type and arrangement of the machine, and varies so widely for different designs of machines that no definite rule for estimating its amount can be given.

To compute the weights of the various parts, multiply their solid contents, in cubic inches, by *.28*, in case of *wrought iron* or *cast steel;* by *.26*, in case of *cast iron;* by *.32*, for *copper;* and by *.30*, for *brass.*

95. Example of Determining Weight-Efficiency.—*Find the weight-efficiency of the toothed-armature shunt-wound four-pole dynamo shown in Fig. 26, page 77.*

Solution.—The weights of the various parts of this dynamo are as follows:

Yoke, 27½″ external diameter, 22½″ internal diameter, 8″ breadth:

$$\left[(27\tfrac{1}{2})^2\frac{\pi}{4} - (22\tfrac{1}{2})^2\frac{\pi}{4}\right] \times 8 \times .28 = \dots\dots\dots \quad 440 \text{ lbs.}$$

4 cores, 6⅝″ diameter, 4″ long:

$$4 \times (6\tfrac{5}{8})^2\frac{\pi}{4} \times 4 \times .28 = \dots\dots\dots\dots\dots\dots \quad 155 \text{ ``}$$

Polepieces and *core-seats* on yoke, approximately, 75 "

Magnet winding (see page 111), 148 lbs., or round: 150 "

Armature. Core, 12″ external diameter; 6⅞″ internal diameter; 10½″ long; slots, 1″ deep.

Provided that the entire height of the slots is occupied by the winding, the dimensions of the wound armature are: External diameter 12″, internal diameter 4⅞″, length 12½″; and its weight is, practically:

$$\left[(12)^2\frac{\pi}{4} - (4\tfrac{7}{8})^2\frac{\pi}{4}\right] \times 12\tfrac{1}{2} \times .28 = \dots\dots\dots\dots \quad 330 \text{ ``}$$

The total weight of the armature core and winding is here computed approximately by considering the wound armature as a hollow cylinder of iron. A more accurate method is to find the exact weight of the armature core, by deducting from the core, with the slots considered as solid, the weight of the iron in the slots, and adding to it the weight of the winding obtained by Par. **38** and Table **13**.

Bedplate, Journals, and *Shaft* (estimated).......	800 lbs.
Aggregate weight of *principal parts*..........	1950 lbs.
Allowance for *accessory parts* (15% of above figure)....................................	300 "
Total weight of machine.........................	*2250 lbs.*

The output of the above dynamo is 125 volts and 240 amperes (see page 88), or *30* kilowatts; hence the weight-efficiency:

$$\mathit{Wt.\ Eff.} = \frac{30,000}{2250} = \mathbf{13.3} \text{ watts per pound.}$$

This being a very high weight-efficiency for a dynamo of the given size and speed, it follows that the machine is economically designed, and would, when built, compare favorably, as to lightness and cost, with existing machines.

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QUESTIONS
ON
THE DESIGN OF DIRECT-CURRENT
DYNAMOS AND MOTORS

THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS.

1. In what form is a problem of generator design usually given?

2. Give the formula for the current strength of a generator if its capacity and voltage are known.

3. State the form in which a problem of motor calculation is usually given.

4. Give the formula for the output of a generator which corresponds to a motor of given horse-power.

5. Express the counter E. M. F. of a motor in terms of the supply voltage.

6. By what formula can the current strength of a motor be found, if its output, its voltage, and its electrical efficiency are given?

7. Find the electrical power equivalent to a motor output of 15 horse-power.

8. What is the average counter E. M. F. of a 2 H. P. motor designed to operate on a 110-volt circuit?

9. Compute the full-load current of a 50 H. P. motor run from a 250-volt circuit.

10. Give the average electrical efficiency of a 3 H. P. motor.

11. What is the average commercial efficiency of a 35 H. P motor?

12. State the four principal forms of armatures.

13. Which of the four types of armatures referred to in the preceding question are most used? Give also the scope of the other types.

14. Name the chief advantage of the ring type of armature.

15. State the advantage of formed armature coils.

16. What is the principal advantage of the drum type of armature?

17. What is the latest practice in the selection of the type for an armature?

18. What is the object of laminating the armature core?

19. In which direction should the armature core be laminated relative to the direction of the magnetic flux and to the direction of rotation?

20. State the disadvantages of armature cores built of iron wire.

21. How are the core discs arranged in armatures of small and of large sizes?

22. What is the usual thickness of the sheet iron employed for core discs?

23. How are the core laminæ insulated from each other?

24. How does the lamination of the armature core affect its magnetic carrying capacity?

25. What is understood by the effective cross-section of the armature core?

26. Name the advantages of toothed armatures.

27. State the disadvantages of toothed armatures.

28. How should the slots of a toothed armature be proportioned so as to avoid the generation of eddy currents in the pole pieces?

29. Name some expedients employed to reduce the eddy current tendency due to improperly proportioned toothed armatures.

30. What are the objections to perforated armatures?

31. Name the chief points to be considered in determining the size of an armature.

32. Give the formula for the peripheral velocity of an armature.

33. Express the diameter of an armature in terms of its peripheral velocity, v, and its revolving speed, n_1.

34. What are the limits of the peripheral velocity in practical machines?

35. Give the average value of v for high-speed ring machines.

36. What is the average peripheral velocity of medium-speed ring machines?

37. State the average of v for low-speed machines.

38. What is the average circumferential velocity of drum armatures?

39. Give the approximate armature velocity for a high-speed ring machine of 25 K. W. capacity.

40. What peripheral velocity should be chosen for a 400 K. W. low-speed direct-connected machine?

41. State the approximate velocity of a 600 K. W. medium-speed ring armature.

42. Give the approximate peripheral speed of a 25 K. W. drum armature.

43. Name the kinds and sizes of machines for which 3,000 feet per minute is a good value for the peripheral velocity.

44. Define the cooling surface of an armature.

45. What portion of its surface do we consider the cooling area of a drum armature? Why not the entire surface of the core?

46. Give the formula for the cooling surface of a drum armature in terms of its diameter and length.

47. What is the formula for the cooling surface of a drum armature, expressed in terms of its diameter and shape ratio?

48. What area is usually considered the cooling surface of a ring armature?

49. Give the formula for the usual case of the cooling surface of a ring armature, if all its dimensions are given.

50. What formula is used for the cooling surface of a ring armature, if only its diameter is given and its shape ratios are assumed?

51. How much cooling surface is needed to dissipate the heat corresponding to 1 watt of power loss?

52. Give the formula for the cooling surface required for a dynamo having a capacity of W watts.

53. What is the average percentage of power loss in a 75 K. W. machine?

54. Give the usual limits of the actual power loss (in kilowatts) of a 200 K. W. dynamo.

55. From Table **3,** Instruction Book, find the usual limits and the average of the power loss in a 10 K. W. dynamo..

56. Give the formula for the diameter of a drum armature having a cooling surface proportional to its capacity W.

57. State the corresponding formula for a ring armature.

58. What value of s should be used in the formula for drum armatures referred to in Question **56?**

59. Give the value of the specific cooling surface employed in connection with the formula for ring armatures referred to in Question **57.**

60. Give the average ratios (**a**) of length to diameter, and (**b**) of radial thickness to diameter, for a 10-foot ring armature, using Table **4,** Instruction Book.

61. From the answer to the preceding question find the average length and radial thickness of a ring armature having a diameter of 10 feet.

62. State the approximate shape ratios of a ring armature 20 inches in diameter.

63. What is the average shape ratio, m, and the length, L_a, of a drum armature 8 inches in diameter?

64 Give the approximate average length of a drum armature having a diameter of 36 inches.

65. What must be the diameter of a 100 K. W. drum armature designed to run at 450 revolutions per minute, in order to have the proper peripheral velocity as given by Table **2**, Instruction Paper?

66. Compute the smallest diameter which the armature, specified in the preceding question, must have in order that its specific cooling surface be at least $s = .7$ square inch per watt, when assuming a percentage of power loss of $k = .04$ and a shape ratio of $m = 1.25$.

67. A 12 K. W. drum armature is to run at a speed of 1,000 revolutions; find the diameter for which both the circumferential velocity and the cooling surface are nearest to the averages given in Tables **2**, **3**, and **4**, Instruction Paper.

68. Determine the diameter of a 300 K. W. direct-driven ring armature for a speed of 150 revolutions per minute both by peripheral velocity and by cooling surface, using the average values of v, s, k, m, and m' given in the tables.

69. Give the length and radial thickness of the armature considered in the preceding example, and compute its actual cooling surface from the dimensions.

70. Determine in a similar manner the cooling surface of the drum armature of Question **67**.

71. From Table **5**, page 17, Instruction Paper, find the shape ratio m of the 7½ H. P. *Crocker-Wheeler* motor, the length of the armature being the dimension marked J, and the diameter being the dimension designated by Y.

72. Using the data given in Table **5**, compute the peripheral velocity of the 3 H. P. *Crocker Wheeler* motor, the armature diameter Y being expressed in inches.

73. What are the smallest and greatest values of the velocity v in the *Edison* bipolar drum machines tabulated on page 18, Instruction Book? State which size machine has the minimum value of v, and for which size v is a maximum.

74. Give the maximum and minimum values of the shape ratio m for *Edison* drum armatures.

75. From Table **7**, Instruction Book, find the average value of the velocity v for *Westinghouse* medium-speed drum armatures.

76. Find a similar average for *General Electric* medium-speed ring armatures, from Table **8**.

77. Give the values of the shape ratios m and m' for No. 1, No. 4, and No. 6 machines of Table **8**, Instruction Book.

78. What are the values of v used in the 2 K. W., 50 K. W., and 600 K. W. *Crocker-Wheeler* multipolar generators (Table **9**)?

79. What are the shape ratios m of the armatures of the machines named in the preceding question?

80. Compute the peripheral velocities of the *General Electric* low-speed generators given in Table **10**.

81. Find the values of the shape ratios m referred to in the preceding question.

82. From dimensions A, C, and D, given in Table **10**, determine the ratios m', of radial thickness of the solid portion of the armature core to the diameter, for *General Electric* low-speed multipolar generators.

83. Compare the two 17.5 K. W. high-speed ring machines given in Table **11**.

84. Make a similar comparison between the two 150 K. W. low-speed machines given in the same table.

85. From the data given in Table **11**, Instruction Book, complete the following table of approximate average speeds of high, medium, and low speed ring dynamos:

TABLE OF AVERAGE RING ARMATURE SPEEDS.

Output, in Kilowatts.	High Speed.	Medium Speed.	Low Speed.
2.5	1600	1100	500
5	1400	1000	400
10			
50			
100			
150			
250			
500	....	....	
1000	....	....	

86. From the figures of Table **12** compile a similar table of average drum armature speeds for .5, 1, 2, 5, 10, 25, 50, 100, and 200 K. W. machines.

87. State the limits between which it is customary to choose the specific cross-section of the armature conductor.

88. What is the specific conductor cross-section usually allowed in armatures for ordinary dynamos?

89. In what class of machines is it expedient to use the lower limit referred to in Question **87**, and in what class of machines is the upper limit of specific cross-section employed?

90. What portion of the total current flows through each armature conductor in a bipolar armature?

91. How is a current in any conductor of a multipolar dynamo related to the total current, (**a**) when opposite coils of the armature windings are cross-connected at the commutator, (**b**) when the brushes are connected in parallel, (**c**) when the coils are connected by a two-circuit winding?

92. A six-pole machine furnishes a total current of 300 amperes; what is the current flowing in each wire, if the winding is cross connected, and if each conductor consists of 2 wires connected in parallel?

93. What must be the gauge of the wire referred to in the preceding question, if a specific area of 800 circular mils per ampere is taken? Use Table **13**, Instruction Book.

94. Given a smooth armature of 9 inches diameter, how many No. 12 B. & S. wires can be wound on it, if the height of the winding space is not to exceed $\frac{1}{2}$ inch, and if one-tenth of the circumference is used for division strips?

95. A smooth ring armature of 30 inches external diameter, 22 inches internal diameter, and 12 inches length, is wound with No. 8 B. & S. wire to a uniform height of $\frac{7}{16}$ inch. Find the number of conductors, the total length of wire and its total resistance, assuming that the entire interior surface is covered by the winding.

96. A toothed armature of 21 inches diameter has 88 slots, each $\frac{3}{8}$ inch wide and $1\frac{7}{16}$ inches deep; how many No. 10 B. & S. wires can be wound on it?

97. Determine the size of conductor required for a 50 K. W. 125-volt bipolar dynamo to be used under ordinary conditions.

98. Find the sectional area required for the armature conductor of a 1200 K. W. 8-pole railway generator (550 volts) for central station use.

99. Compute the gauge of the armature wire for a 30 H. P. bipolar elevator motor to run on a 220-volt circuit.

100. What size wire should be used for a 12 K. W. 4-pole arc-light generator delivering 10 amperes and having a two-circuit winding?

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101. Upon what does the number of conductors depend which can be placed upon an armature of given diameter?

102. Give the average winding height of a 6-inch smooth drum armature.

103. What is the average height to which a 50-inch smooth ring armature is usually wound?

104. Give the average depth of slot of a 20-inch toothed armature.

105. Give a simple formula expressing the cross-section of the winding space on a smooth-core armature.

106. What average percentage of the total winding space is occupied by insulation, etc., in an ordinary smooth-core armature machine?

107. State formula giving the available inductor space on a smooth-core armature.

108. Give formula for total number of conductors on a smooth-core armature, if the diameter of the core, the winding height, and the thickness of the wire are known.

109. State the formula for the approximate total number of conductors on a toothed armature, if the armature diameter, the winding height, and the size of wire are given.

110. What is the usual practice with reference to the number of commutator segments for dynamos of various voltages?

111. How is the final number of wires per layer in a smooth-core armature found?

112. How is the arrangement of armature inductors adjusted, when the final number of wires per layer referred to in the preceding question is found about half-way between two whole numbers?

113. How can a given winding space be utilized to the best advantage, electrically?

114. Give average number of slots for toothed armatures of various diameters.

115. By means of formula **16,** find the approximate number of No. 12 B. & S. wires that can be wound upon a smooth drum armature 4½ inches in diameter, and verify result by use of Table **13,** Instruction Book.

116. How many No. 9 B. & S. wires can be placed on a smooth ring armature having an external diameter of 30 inches? Use both formula (**16**) and Table **13.**

117. Determine the number of No. 5 B. & S. wires which may be put on a 60-inch smooth ring armature.

118. Compute the approximate number of No. 7 B. & S. wires on a 32 inch toothed armature, using formula (**17**), Instruction Book.

119. Check the result obtained in answer to the preceding question by means of the data given in Table **13.**

120. Check the answer to Question **118** by means of Tables **14** and **15.**

121. State the fundamental relation between the rate of cutting magnetic lines and the voltage generated.

122. What is the voltage generated per foot of armature inductor under unit conditions?

123. What are termed the idle conductors on an armature, and what percentage does their number usually bear to the total number of conductors?

124. Give the formula for the total E. M. F. generated in an armature.

125. By transformation of the E. M. F. formula referred to in the preceding question, give the expression for the length of armature inductor required to produce a certain voltage.

126. Upon what does the gap induction in a dynamo depend?

127. How can Table **16** be used for machines in which a strong field is desired?

128. How is Table **16** used in case of electroplating machines, battery motors, and incandescent generators?

129. From Table **16** find the approximate gap density for a 25 K. W. smooth armature bipolar dynamo having cast iron polepieces.

130. What field density should be chosen for the machine referred to in the preceding question, if it had a toothed armature and cast steel pole shoes?

131. Give the average field induction which should be taken for a 50 K. W. multipolar dynamo with smooth armature and wrought iron polepieces, if a strong magnetic field is required.

132. What gap density is to be used for a 10,000-light multipolar incandescent generator having a toothed armature and steel polepieces?

133. Give the average field density employed for the machine referred to in the preceding question, in case of a smooth-core armature and strong field.

134. Express the length of the armature core in terms of the number of inductors and of their active length.

135. If an armature has N inductors and n_p bifurcations, what is the number of inductors effective in generating the total voltage?

136. Give the formula for the armature flux in terms of the electrical data of the machine.

137. Express the armature flux in terms of the field density and of the dimensions of the armature.

138. The total armature flux of a 6-pole dynamo being 9,000,000 lines, what is the flux per pole?

139. Find the armature flux of a bipolar 60 K. W. 130-volt generator, having 100 armature inductors and running at a speed of 700 revs. per min.

140. By the use of formula (**22**), compute the gap induction of the machine given in the preceding example, provided that its armature has a diameter of 15 inches and a length of 24 inches.

141. A 300 K. W. 4-pole railway generator gives 550 volts at 4 0 revs. per min.; its frame is of cast iron, and it has a toothed ring armature, 44 inches in diameter and 27 inches long, which is wound with 360 conductors arranged in 4 circuits. Find the armature flux by formula (**21**) and check the result by formula (**22**), using Table **16**.

142. Give formula for radial depth of armature core.

143. What is the average practical flux density in the armature core, (**a**) for ordinary bipolar machines, (**b**) for ordinary multipolar dynamos, (**c**) for arc lighting machines, (**d**) for low-voltage machines, and (**e**) for alternators?

144. The armature of a bipolar incandescent dynamo is 12 inches long; the armature flux is 6,000,000 lines. How deep should the core be made?

145. Compute the proper breadth of cross-section for the armature of a 4-pole arc lighting machine from the following data: Diameter, 23 inches; length, 9 inches; gap induction, 15,000 lines per square inch.

146. Show how to find the radial depth in the preceding example, if the length of the armature is not given.

147. Find the radial depth of the armature core of an 8-pole railway generator, having 2,400 armature conductors, if at 175 revs. per min. its voltage is 550, and if the length of the armature is 13¼ inches.

148. What should be the internal diameter of a 6-pole ring armature whose external diameter is 17 inches and whose length is 5 inches, if the total armature flux is 2,700,000 lines?

149. Give the formula for the total length of conductor on a drum armature.

150. What are the usual limits of the numerical value of the factor *k* in the formula referred to in the preceding question?

151. Compute the average total length of wire on a smooth drum armature, 8 inches in diameter and 15 inches long, if its winding consists of 66 coils, each having 2 turns.

152. What is the total length of conductor of a toothed drum armature, 8 inches in diameter, 14 inches long, having 36 slots, each holding 8 wires, the depth of the slots being 1 inch?

153. Define a spirally wound armature.

154. State the formula for the total length of wire on a spirally wound ring armature.

155. A spirally wound smooth-core armature has an external core diameter of 18 inches, and an internal core diameter of 11 inches, and a length of 15 inches; it contains 560 conductors occupying an average height of ½ inch; what is the average total length of wire?

156. Find the approximate total length of wire on a 27-inch armature, 12 inches long, which is wound with 144 formed coils, each consisting of 4 turns and spanning one eighth of the circumference.

157. A 14-pole toothed armature is wound with formed coils. Its diameter is 7 feet; its length, 17½ inches; it has

192 slots, 6 conductors per slot. Compute the approximate total length of wire.

158. If a wire having a resistance of 16 ohms is divided into 8 equal parts, what is the joint resistance of the 8 pieces of wire when connected in parallel?

159. Express the armature resistance in terms of the total resistance of the armature wire and of the number of bifurcations.

160. Give the formula for computing the armature resistance from the total length of wire on the armature.

161. What is meant by the resistivity of a wire?

162. How is the resistivity at a temperature higher than 20° C. found?

163. What is the rule for computing the resistivity of a warm wire, when the temperature is given in Fahrenheit degrees?

164. By what factor must the resistivity at 68° F. be multiplied to obtain the resistivity at 160° F.?

165. What is the resistivity of No. 9 B. & S. wire at 50° C.?

166. Find the resistance at 80° C. of the armature given in Example **151,** if each conductor consists of 4 No. 13 B. & S. wires.

167. What will be the resistance in the previous case, if the armature, in order to produce double the voltage and one-half the current output, is connected up so that each conductor consists of only 2 No. 13 wires?

168. Give the resistance of the armature referred to in Question **166** for the case that it is wound in 4 parallel circuits suitable for a 4-pole field.

169. Compute the resistance at 76° C. of a bipolar drum armature 23¾ inches in diameter, 26½ inches long, and wound with 40 coils, each coil consisting of 1 turn of 20 No. 7 B. & S. wires.

170. A 6 pole ring armature having an external diameter of 42 inches, an internal diameter of 34 inches, and a length of 11 inches is wound spirally with 600 turns of 2 No. 6 B. & S. wires, in two layers. Find its resistance at 60° C.

171. What would be the resistance of the armature in the preceding example, if it were wound with 1,200 turns of 1 No. 6 B. & S. wire so as to give double its previous voltage in a 4-pole field?

172. How can the armature design be checked with reference to the heating limit?

173. If the temperature increase of the armature is found excessive, how must the armature be re-designed?

174. Give formula for computing the power loss in the armature winding.

175. How can the exact amount of the shunt current in a completed machine be computed?

176. Tabulate the average factors by which the external current of shunt and compound wound generators and motors of various capacities must be multiplied, in order to obtain the current flowing in the armature.

177. What is the formula for the power loss by hysteresis?

178. What does the hysteresis factor express?

179. How can the hysteresis factor for any given flux density be calculated?

180. What is the value of the hysteresis factor for a flux density of 77,500 lines per square inch?

181. Find the hysteresis factor for a density of 142,000 lines per square inch.

182. How is the frequency of a dynamo obtained?

183. Give formula for the mass of the armature core.

184. By what formula is the power loss by eddy currents calculated?

185. What is the eddy current factor, and upon what does its magnitude depend?

186. Give the eddy current factor for sheet iron, 20 mils thick, at a flux density of 94,000 lines per square inch.

187. What is the eddy current factor for .012-inch sheet iron at 85,000 lines per square inch?

188. Compute the eddy current factor at 88,000 lines for a thickness of lamination of $\frac{1}{32}$ inch.

189. How is the specific power loss in the armature obtained?

190. Tabulate the average temperature increase of drum and ring armatures corresponding to various values of the specific cooling surface.

191. What is the probable average temperature rise of a ring armature, for which the value of the specific cooling surface has been found to be .85?

192. What is meant by the circumferential current density of an armature?

193. Give the formula for the circumferential current density of any armature.

194. Compile the average values of the temperature rise corresponding to various values of the circumferential current density.

195. If the circumferential current density of a high-speed armature has been found to be $c = 335$, what will be the probable average temperature rise?

196. Find the probable temperature increase of a bipolar drum armature of which the following data are known: Output (constant potential), 250 volts, 100 amperes; speed, 1,300 revs. per min.; diameter, 8¾ inches; length, 16½ inches; inside diameter of disc, 3½ inches; thickness of sheet iron, .020 inch; winding, 66 coils of 2 turns of No. 6 B. & S. wire; resistance, at 20° C., .06 ohm.

197. Predetermine the approximate average temperature rise of a 100 K. W. ring armature, 66 inches in diameter, which generates 150 volts at 175 revs. per min., and which is wound with 944 conductors connected in 8 circuits.

198. A smooth ring armature, having an external core diameter of 106 inches, an internal diameter of 95¾ inches, and a length of 26 inches, generates a current of 800 amperes at 500 volts, when running at a speed of 100 revs. per min.; the sheet iron used for its core disc has a thickness of .020 inch; its winding consists of 1,632 turns of 2 No. 5 B. & S. wires; the field magnet has 12 poles and is compound wound. What temperature increase may be expected under average conditions?

199. A bipolar toothed armature 38½ inches in diameter has 138 slots, $\frac{7}{16}$ inch wide by $1\frac{9}{16}$ inch deep; its length is 10 inches; the radial depth of its solid portion is 6¾ inches; its core is built up of .015-inch sheet iron; its winding consists of 46 coils, each coil having 9 turns of 20 No. 12 B. & S. wires; the coils are wound spirally, 60 wires being placed in each slot. When running at 200 revs. per min., the output of this armature is 50 K. W., at 125 volts; to what average final temperature is it expected to heat, if the temperature of the dynamo room is 18° C.?

200. Compute the temperature increase of the armature of a 16-pole compound-wound railway generator from the following data: Output, 2,000 kilowatts, at 540 volts; speed, 70 revs. per min.; external diameter of toothed core, 144 inches; diameter at bottom of slots, 137¾ inches; internal diameter of core, 124 inches; length of core, 32 inches; thickness of discs, .018 inch; winding, 2,016 copper bars, ⅞ inch high by ¼ inch wide, arranged in 336 slots, $\frac{11}{16}$ inch wide; resistivity of armature conductor, .0000375 ohm per foot; interconnection of bars effected by end connectors spanning one-sixteenth of circumference.

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DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS.

201. What is the almost universal modern practice in regard to the adoption of the bipolar and multipolar forms for dynamos of various outputs?

202. Name the advantages of the multipolar form over the bipolar.

203. What are the disadvantages of multipolar machines?

204. Show the saving of material effected in the multipolar construction by comparing a 4-pole frame with a bipolar frame for the same armature.

205. Compare in the same manner as in the preceding question an 8 pole machine with an equivalent one of the bipolar type.

206. If a total flux of 2,400,000 lines is required for an armature of given diameter, what must be the carrying capacity of the armature cross-section for a bipolar, 4-pole, and 8-pole machine, respectively ?

207. Neglecting magnetic leakage, how many lines are carried by each magnet core and by the yoke section of the bipolar, 4 pole, and 8-pole construction in the case considered in the preceding question?

208. Give the formula for the frequency of magnetic reversal in a dynamo-electric machine.

209. What is the frequency of an 8-pole machine when running at 500 revolutions per minute?

210. What are the usual limits of the frequency in direct-current machines?

211. Give the usual average values of the frequencies for low-speed, medium-speed, and high-speed direct-current machines, respectively.

212. Give formula for obtaining the proper speed of a machine corresponding to a given frequency.

213. What must be the speed of a 6-polar dynamo, if a frequency of 15 cycles is desired?

214. Compute the maximum permissible speed of an 8-pole direct-current machine.

215. By transposition of the terms in the frequency formula deduce an expression for the proper number of pole-pairs for a dynamo.

216. From the formula given in answer to the preceding question, find the number of poles for a medium-speed machine running at 400 revolutions per minute.

217. State the proper number of poles for a low-speed 125-revolution machine, by means of Table **23**, Instruction Book.

218. Between what limits may the pole number be selected for a 175-revolution high-speed dynamo?

219. For what kind of machines is the bipolar type almost always adopted?

220. In what machines is the 4 pole construction generally used?

221. Name the kinds of machines in which 6 poles or more are employed.

222. What determines the cross-section of a dynamo magnet frame?

223. Give formula for the cross-section of the field frame, and state the meaning of the symbols used.

224. What are the usual limits of the leakage factor for bipolar toothed-armature machines?

225. Between what limits does the leakage factor ordinarily range in bipolar smooth armature machines?

226. Give the usual range of the leakage factor for multipolar ring-type machines having a toothed armature.

227. Between what values does the leakage factor of multipolar smooth-armature dynamos usually vary?

228. State the limits between which the flux density for wrought iron and cast steel should be chosen.

229. What are the best values of the flux density in cast iron?

230. How is the core area of a multipolar machine obtained from the formula referred to in Question **223**?

231. By what number must the total frame area of a multipolar ring-type dynamo be divided to give the cross-section of the yoke?

232. What relation does the yoke-section usually bear to the core-section in multipolar types, if the same material is used for both?

233. Show a multipolar type in which the yoke-section is equal to the core-section.

234. What is the usual relation between core-area and yoke-area in the bipolar types, provided that cores and yoke are of the same material?

235. Sketch a bipolar type in which the yoke-section is only one half the core-section.

236. Tabulate the average values of the leakage factor for the various sizes of the most common types of dynamos, according to Table **24**, Instruction Book.

237. What is the approximate leakage factor of a high-speed 5 K. W. inverted horseshoe type machine, having a smooth armature and cast iron field frame?

238. State the approximate leakage factor of a low-speed 25 K. W. dynamo of the multipolar ring type, having a toothed armature and a cast steel frame.

239. Why is the leakage factor for one and the same magnet frame smaller with a toothed than with a smooth armature?

240. Give reason why a wrought iron or cast steel magnet frame for a given armature results in a machine of smaller leakage than a cast iron frame.

241. If two machines of the same type and construction are designed to have equal output at different speeds, which one will have the greater factor of magnetic leakage, and why?

242. Why is the leakage factor of small machines greater than in large dynamos of the same type?

243. Give rules for the length of the magnet cores in bipolar machines having toothed armatures.

244. State rules similar to those of the preceding question for the length of field cores of bipolar smooth-armature machines.

245. How should the magnet cores of smooth-armature multipolar machines be proportioned ?

246. Give the ratios of length to diameter of magnet cores for large, medium, and small multipolar machines with toothed armatures.

247. Why is it necessary to make the magnet cores longer for smooth-armature machines than for those having toothed armatures?

248. The proper core-section for a bipolar machine having been found to be 50 square inches, what is the average length of each magnet core, if the machine has a smooth armature?

249. What would be the proper length of the magnet cores in the preceding example, if the machine has a toothed armature?

250. Give the average length of the magnet cores for a large 8-pole smooth-armature machine, if it has been found that a total frame area of 1,400 square inches is required.

251. Name the conditions which determine the length of the air gap.

252. Between what limits does the radial depth of the air gap usually range in machines with toothed armatures?

253. State the average radial clearances allowed in very small and in very large smooth-armature machines.

254. What should be the bore of the polepieces for a toothed armature, 41½ inches in diameter?

255. The height occupied by the winding of a smooth-core ring armature, 6 feet in diameter, is ½ inch; find the diameter of the bore of the polepieces, when allowing ⅛ inch for core insulation, binding wires, etc.

256. A smooth drum armature, having a core diameter of 13½ inches, is wound with 4 layers of No. 10 B. & S. wire; the core insulation consists of two layers of mica·cloth, .025 inch thick each, and the binding bands are made up of No. 20 B. & S. phosphor-bronze wire and insulated from the winding by sheet mica, .012 inch thick; give the diameter to which the poles should be bored.

257. Determine the dimensions of the magnet cores for an inverted horseshoe-type dynamo similar to Fig. 25, Instr. Paper, having a smooth drum armature, 7 in. in diameter, 12 inches long, which is wound with 96 turns and is required to generate 125 volts and 120 amperes at 1,500 revolutions per minute. Assume the leakage factor to be 1.30, and take a density in the frame of 80,000 lines per square inch.

258. What would be the dimensions of the cores, if the armature in the preceding example had a toothed instead of a smooth core, the armature dimensions and number of conductors remaining the same?

259. Find the dimensions of the polepieces and yoke of the machine considered in Question **257**, and show a cross-section of the complete magnet frame, making the sketch one-quarter size; insert the dimensions of the various parts; show the inverted horseshoe type.

260. Make a sketch similar to the one asked for in the preceding question, for the machine of Question **258**, having a toothed armature. Draw to the same scale as before and give all the dimensions, assuming the slots to be ¾ inch deep.

261. How is the yoke of a bipolar machine usually dimensioned?

262. Give a formula expressing the height of the yoke of a bipolar machine in terms of the core diameter, provided that the yoke is of the same material as the cores.

263. The diameter, D_m, of the magnet cores and the length, L_a, of the armature being given, express the thickness of the middle section of the polepieces of a bipolar dynamo, supposing the polepieces to be made of the same material as the cores.

264. What effect has slotting of the core upon the dimensions of a small ring armature?

265. Compute the diameter and length of cast steel magnet cores for a 6 pole machine having a smooth armature;

the flux required is 20,000,000 lines, and the factor of leakage 1.28.

266. Find the dimensions of the magnet frame of a 4-pole machine for which the following data are given: Armature, 40 inches in diameter, 25 inches long, having 84 slots, $\frac{3}{16}$ inch wide and $1\frac{3}{4}$ inches deep; useful flux, 38,000,000 lines; factor of leakage, 1.3; magnet frame to be entirely of cast iron, cores to have rectangular cross-section; width of magnet cores and yoke to be equal to length of armature core.

Note:—To find the length of rectangular cores, determine the diameter of the equivalent circular cross-section, and apply the rules given in Par. **56**, Instruction Book.

267. Give sketch, drawn to scale, showing the complete magnetic circuit of the machine considered in the preceding example.

268. Name the advantages of circular magnet cores over rectangular and elliptical magnets.

269. In what type of machines is the employment of rectangular cores justified, and why?

270. State the only exceptional case in which a practical dynamo designer would employ curved magnet cores.

271. Give the formula for the total magnetizing force of a dynamo, and name the symbols employed.

272. State the fundamental law of the magnetic circuit.

273. Define permeance.

274. How is the permeance of a magnetic path expressed?

275. Give the formula for the magnetomotive force, in gilberts, required to produce a certain density in an iron path of given length.

276. Express the ampere-turns required for an iron path, if metric units are employed.

277. What is the formula for the ampere-turns of an iron path, in English units?

278. State the formula for the ampere-turns of an air path, if its length and density are given in metric units.

279. Give the expression for the ampere-turns of an air path in English units.

280. Define specific magnetizing force.

281. Give formula for the ampere-turns required for any portion of a magnetic circuit, if its length and specific magnetizing force are given.

282. State an approximate rule, used in preliminary calculations, for finding the ampere-turns required for compensating armature reaction.

283. Inspect closely the magnetizing curves of annealed wrought iron and ordinary cast iron (Fig. 27, Instruction Book), noting three or four characteristic points on each curve, and then plot these curves by locating the points so noted in a roughly drawn co-ordinate system and connecting the same by free hand.

284. What is the specific magnetizing force for soft cast steel at a density of 55,000 lines per square inch?

285. Give the specific magnetizing force of annealed wrought iron, if its density is 106,000 lines per square inch.

286. From Table **26**, Instruction Book, determine the ampere-turns required for 25 inches of soft cast steel, if the density is 92,500 lines per square inch.

287. State the influence of the armature current upon the magnetic field.

288. Give formula for the demagnetizing number of ampere-turns of a smooth armature.

289. How can the angle of field distortion be approximately determined in case of a smooth armature?

290. How must the formula referred to in Question **288** be modified in case of a toothed armature?

291. What correction is necessary to apply the formula of Question **288** to a perforated armature?

292. State the average formula for the total number of compensating ampere-turns in case of wrought iron or cast steel polepieces.

293. Give the average formula for the total number of compensating ampere-turns in case of cast iron polepieces.

294. Determine the magnetizing force required for the bipolar smooth armature machine shown in answer to Question **259**, provided that the internal diameter of the armature discs is 3 inches.

295. The magnet frame of a bipolar dynamo is composed of wrought iron cores and yoke, and cast iron polepieces; the diameter of the cores is $14\frac{5}{8}$ inches; the cross-section of the yoke is equal to that of the cores; the section of the polepieces is 408 square inches, that of the armature core is 170 square inches, and the gap area is 440 square inches; the length of the magnetic circuit in the cores and yoke is 80 inches, in the polepieces $28\frac{1}{2}$ inches, in the armature $12\frac{1}{2}$ inches, and in the air gaps $1\frac{1}{2}$ inches; the armature flux is 11,000,000 lines; the factor of leakage is 1.3; the armature is wound with 50 turns; current output, 480 amperes; polar embrace, 75 per cent. Compute the exciting power required.

296. Find the number of ampere-turns required to excite the machine shown in answer to Question **260**, assuming the density in the teeth to be 100,000 lines per square inch, and the density in the solid portion of the armature core, 85,000 lines per square inch.

297. Assuming the machine given in Question **266** to be wound with 336 armature turns and having a current output of 600 amperes, what will be the exciting power required? Determine the flux densities in the air gaps and in the tooth-section for the dimensions shown in answer to Question **267**; to find the former, add 50 per cent. to the gap density at the pole faces to allow for concentration of the lines due to the teeth; and to obtain the latter, divide the armature flux by the tooth-section at the root of the teeth.

298. A 16-pole ring-type generator for 540 volts and 3,700 amperes has the following dimensions: External diameter of armature core, 144 inches; internal diameter, 124 inches; length, 31 inches; actual length occupied by the discs, 26½ inches; number of slots, 336; width of slots, 11/16 inch; depth of slots, 3⅛ inches; winding, 6 turns of armature conductor per slot; magnet frame, cast steel; cores, rectangular, 25 × 13 inches in cross-section, 16 inches long; yoke, 191 inches in diameter, 32 inches wide, 5 inches thick; pole plates, 32 inches long, 20 inches wide, 1½ inches thick in center, embracing angles of 16° each; bore of polepieces, 144⅞ inches. The armature flux required to produce the rated output is 190,000,000 lines; leakage factor, 1.15. Calculate the ampere-turns necessary for the excitation of this machine, if the average flux density in the air gap is 50 per cent. in excess of the density at the pole faces, and if the mean length of the path in the air gap is 50 per cent. greater than the distance between pole face and armature.

299. Determine the magnetizing force required for a 10 pole dynamo from the following data: *Type:* radial inner-pole or star type, having cores supported radially from a central yoke in the form of a star. *Material:* cores and polepieces, wrought iron; yoke, cast iron. *Armature:* external core diameter, 120 inches; internal core diameter, 109½ inches; length, 20 inches; winding, 1,700 turns of rectangular copper bar. *Magnet frame:* diameter of polepiece circle, 107 inches; thickness at center of pole shoes, 3½ inches; polar embrace, 80 per cent.; magnet cores, rectangular cross-section, 12 inches thick, 19¾ inches wide, 16½ inches long; yoke, hollow decagonal prism, internal diameter 45 inches, length 23 inches, radial depth 11 inches. Current output, 1,400 amperes; armature flux, 90,000,000 webers; leakage factor, 1.2. Allow 25 per cent. in length of air gap for distortion of lines.

300. Find the ampere-turns required for a 6-pole ring-type 2,500-ampere generator, the following data being given: External diameter of armature, 96 inches; internal diameter, 60 inches; length, 34 inches; length actually occupied by iron discs, 28½ inches; number of slots, 264; size of slots, 2¾ × $\frac{9}{16}$ inch; winding, 2 conductors per slot, connected in drum fashion (by means of formed face connectors at end surfaces of armature core); magnet cores, wrought iron, 30¾ inches in diameter, 20 inches long, provided with wrought iron pole shoes, 34 × 34 × 2⅛ inches; yoke, cast steel, 161 inches in diameter, 38 inches wide, 10 inches deep; bore of pole-pieces, 96¾ inches; armature flux, 170,000,000 lines; factor of leakage, 1.18. Assume average gap density to be 1½ times the density at pole faces, and take length of air space 1½ times the actual gap distance.

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THE DESIGN OF DIRECT-CURRENT DYNAMOS AND MOTORS

301. Name the four methods of winding magnets for direct-current dynamos and motors.

302. How are constant-current arc-light generators excited?

303. How are the magnet coils of railway motors arranged?

304. How may direct-connected or geared motors be wound if they are intended for fairly constant load?

305. What winding is used for variable-speed motors?

306. What method of excitation is employed for constant-spee motors with variable load?

307. How are constant-voltage generators wound?

308. How must motors be wound if a strong starting torque is required?

309. What winding is used for constant-potential generators driven by power of widely varying speed?

310. What winding should be employed for motors required to run with constant speed at varying load?

311. One of two similar magnet cores is wound with 250 turns of wire and excited by a current of 15 amperes; the other is wound with 5,000 turns and excited by a current of $\frac{3}{4}$ of an ampere; which is the stronger magnet?

312. How does differential winding differ from ordinary compound winding?

313. Give formula for the number of turns of a series winding.

314. State rule for proportioning the size of wire for a series winding.

315. What sizes of wire are usually employed for the magnet winding of series arc-lighting machines?

316. Give the values of the specific cooling surface to be allowed for temperature rises of 20°, 30°, and 40° C., respectively.

317. Upon what facts is the calculation of the size of wire for a shunt winding based?

318. Give the formula for the approximate warm resistance of a copper wire of given length and diameter.

319. Why does the number of ampere-turns of a shunt magnet remain the same, irrespective of the number of turns, as long as the same size of wire is employed?

320. What formula is used for calculating the cross-section of a shunt wire? Explain the symbols employed.

321. How is the resistance of the field regulator of a shunt machine taken into account in determining the size of the magnet wire?

322. How does the shunt-voltage, entering the formula referred to in Question **320**, compare with the output voltage of a multipolar machine in which all field coils are connected in series?

323. How is the voltage between terminals of shunt winding determined from the output voltage, in case the field coils are connected in groups?

324. Give the value of the shunt voltage for a 500-volt, 8-pole ring type generator if its magnet winding is arranged in 2 groups of 4 coils each, allowing 12 per cent. of the voltage for overcoming regulator resistance.

325. What would be the shunt voltage, if all the coils of the machine referred to in the preceding question were connected in parallel?

326. The size of the shunt wire for a machine having been determined by means of formula (**49**), Instruction Book, what will be the consequence of employing too small a number of turns of this wire?

327. Give formula for the permissible power loss corresponding to a given temperature increase of a magnet.

328. What is the formula for the shunt current which causes a prescribed rise of temperature in a magnet of given size?

329. Express the maximum shunt current in case the temperature increase is limited to 50° C.

330. From Table **27**, Instruction Book, find the approximate winding height of a cylindrical magnet, 9″ in diameter, when used for a multipolar machine.

331. What is the approximate depth of winding on a 2½″ by 4¾″ rectangular core for a bipolar machine?

332. Compute the approximate length of the mean turn on a bipolar magnet 20 inches in diameter.

333. Find the approximate average length of turn on a 6½″ by 17″ multipolar magnet.

334. Determine the cooling surface of a bipolar magnet, 12″ in diameter and 18″ long, taking the external surface and both end surfaces of the coil.

335. Figure the cooling surface of a multipolar rectangular magnet, 4½″ by 12″ in cross-section, 6″ long, including but one of its end surfaces into the cooling surface.

336. Required the cooling surface of an oval magnet whose cross-section consists of a 4-inch square enclosed between two semi-circles, and whose length is 8 inches; the magnet is intended for a bipolar machine and only one of the end surfaces is to be taken into account for cooling.

337. The total number of ampere-turns required for normal load being given, how is the number of series ampere-turns of a compound dynamo found?

338. Give approximate formula for the total E. M. F. of an ordinary compound dynamo.

339. What is the formula for the approximate total E. M. F. of a 5 per cent. over-compounded dynamo?

340. How is the cross-section of the series field wire of a compound dynamo determined?

341. In which case must the size of the series wire, obtained by the rule referred to in the preceding question, be increased?

342. By means of Table **28**, Instruction Book, determine the number of turns of No. 8 wire that can be put in each layer of a coil 12½″ long.

343. How many turns of No. 14 wire can be wound in a coil space 8¾″ long and 1½″ high?

344. A magnet of 17″ diameter is wound with 15,000 turns of No. 19 B. & S. wire to a height of 1⅛ inches; find the bare and covered weight of the wire and its resistance at 20° C.

345. Calculate a series winding for the machine given in Question **295** (Part 3), supposing that its armature is wound for 5,000 volts and 10 amperes, and assuming that the magnetizing force required for its excitation was obtained as 20,000 ampere-turns; the length of each magnet core is 22 inches; allow a wire cross-section of 1,650 circular mils per ampere.

346. The machine considered in Question **295** is to be shunt-wound for an output of 125 volts and 480 amperes; the winding to be calculated for a magnetizing force of 20.000 ampere-turns and a temperature increase of 20° C.; depth of magnet winding 1½ inches; allow a drop of 15 per cent. for regulating resistance. and take as cooling surface the cylindrical portion of the magnets only.

347. Compute the winding in case it is desired to over-compound the machine given in the preceding example for a line loss of 6 per cent.; both the series and the shunt coils to be connected in series; limit of temperature rise, 25° C.; data for magnetic circuit given in Question **295**; speed, 700 revolutions per minute; the armature is drum-wound and has a resistance of .01 ohm.

348. Calculate a shunt winding for the 2,000 K. W. railway generator given in Question **298**; temperature rise, 30° C.; percentage of E. M. F. absorbed by regulating resistance, 10 per cent.; all magnet coils connected in series; exciting power required, 33,000 ampere turns.

349. The machine of the preceding example is to be over compounded for a loss of 5 per cent ; temperature increase, 35° C.; all the series coils to be connected in parallel, all shunt coils in series; dimensions of machine and magnetic data same as in Question **298**; speed, 70 revolutions per minute; number of armature conductors, 2,016; armature resistance, .002 ohm.

350. A four-pole 25-K.W. direct-driven 150-volt generator is designed as follows: *Armature*, smooth ring. 27" external diameter, 19¼" internal diameter, 12¾" long; winding, 144 coils of 5 turns each; resistance, .036 ohm; length of magnetic path in armature core, 15". *Yoke*, cast iron, octagonal shape, 54" across flats; width, 11½"; radial thickness, 6"; length per magnetic circuit, 33". *Magnets*, cast steel ; diameter, 9"; length, 5¾". *Pole-pieces*, cast steel ; bore, 28¼"; pole angle, 63°. Speed, 300 revolutions per minute; factor of magnetic leakage, 1.3. Compute a shunt winding for a 40° C. rise, allowing 15 per cent. of output E. M. F. for shunt regulator, and taking as cooling area of the coils their cylindrical surface and one end surface. The four shunt coils to be connected in series.

351. Required a 5 per cent. over compound winding for the machine given in the preceding question. Temperature rise, 45° C.; all coils of both series and shunt winding to be connected in series.

352. Assuming that the magnetizing force required for the generator given in Question **300** was found to be 42,000 ampere-turns, determine a shunt winding for a temperature increase of 30° C, allowing 10 per cent. of the terminal E. M. F., which is 600 volts, for regulating resistance; coils connected in series.

353. From the data given for a 1,500 K. W. railway generator in Question **300**, compute a compound winding for a rise of 25° C., provided that the speed is 250 revolutions per minute and the armature resistance .0024 ohm. The series coils to be connected in two groups and the shunt coils in three groups.

354. Define electrical efficiency.

355. Define commercial efficiency.

356. Define gross efficiency.

357. Give the general formula for the electrical efficiency of a generator.

358. State the general formula for the electrical efficiency of a motor.

359. By what formula is the electrical efficiency of a series-wound generator calculated?

360. Give formula for the electrical efficiency of a shunt-wound generator.

361. Give formula for the electrical efficiency of a compound-wound generator.

362. How do the efficiency formulas for a motor differ from the corresponding formulas for a generator?

363. Express the armature current of a shunt or compound-wound generator, and that of a shunt or compound-wound motor, in terms of the terminal and shunt currents.

364. State the usual limits of the electrical efficiency of modern machines.

365. Define the intake and output of dynamo-electric machines.

366. Give the general formula for the commercial efficiency of a generator.

367. Give the general formula for the commercial efficiency of a motor.

368. Give the formula for the commercial efficiency of a compound wound generator.

369. Give the formula for the commercial efficiency of a shunt-wound motor.

370. By means of Table **29**, Instruction Book, find the approximate power-loss by friction in a 35 K.W. dynamo.

371. Between what limits does the commercial efficiency of modern machines usually range?

372. Upon what does the commercial efficiency of a dynamo depend?

373. Give formula for the commercial efficiency of a belt-driven generator, if the data for computing the mechanical power transmitted by its belt are known.

374. State the average percentage of power loss in a horizontal dynamo belt.

375. How is the gross efficiency of a dynamo-electric machine obtained?

376. Give the practical limits of the gross efficiency of modern dynamos.

377. Define the weight-efficiency of a dynamo.

378. What does a high weight-efficiency indicate?

379. Give the usual limits of the weight-efficiency for low, medium, and high speed dynamos, respectively.

380. State the weights per cubic inch of wrought iron, cast iron, copper, and brass.

381. Give the average percentage by which the weight of the principal parts (magnet frame, armature windings, bearings and bed, or brackets) of a high-voltage machine must be increased to allow for accessory parts.

382. By what average percentage must the weight of the principal parts of a low-voltage machine be increased to obtain its total weight?

383. Name an approximate method for computing the weight of a toothed armature.

384. Describe the accurate method of calculating the weight of a toothed armature core.

385. Compute the electrical efficiency of a series-wound 25 arc-light generator (1,250 volts, 10 amperes), whose armature resistance (warm) is 5 ohms, and whose field resistance is 6 ohms.

386. A shunt-wound 150-K.W. 250-volt generator has an armature resistance of .01 ohm, a field resistance of 42 ohms, and a regulator resistance, at normal output, of 8 ohms; determine its electrical efficiency.

387. Find the electrical efficiency of a compound-wound, 125-volt, 500-watt generator, if its armature resistance is 3 ohms, its series field resistance 1.5 ohms, and its shunt resistance 312 ohms.

388. What is the electrical efficiency of a $\frac{1}{2}$ H.P. series motor, taking 4 amperes at 125 volts, if its armature has a resistance of 4.3 ohms and its field a resistance of 1.2 ohms?

389. Calculate the electrical efficiency of a shunt-wound 500-volt motor which takes 12 amperes and has an armature resistance of 2.65 ohms, and a magnet resistance of 943 ohms.

390. The armature resistance of a compound-wound motor is .085 ohm, its series field resistance .025 ohm, and its shunt resistance 88 ohms; the motor consumes a current of 80 amperes on a 220-volt circuit; find its electrical efficiency.

391. Find the commercial efficiency of the arc-light generator of Question **385**, if it has a hysteresis loss of 275 watts, and an eddy current loss of 50 watts.

392. Required the commercial efficiency of the 150 K.W. shunt dynamo given in Question **386**; its hysteresis loss is 1,100 watts and its eddy current loss is 130 watts.

393. The power absorbed by hysteresis and eddy currents in the 500-watt compound-wound generator referred to in Question **387** is 13 watts; what is its commercial efficiency?

394. The ½ H.P. series motor of Question **388** has a total iron loss of 12 watts; determine its commercial efficiency.

395. Compute the commercial efficiency of the shunt motor referred to in Question **389**, if its iron losses are known to be 60 watts.

396. What is the commercial efficiency of the compound-wound motor described in Question **390**, if its hysteresis loss is 200 watts and its eddy current loss is 50 watts?

397. Find the commercial efficiency of a 75 H.P. motor from the following test: E. M. F. of supply circuit, 440 volts; current taken by motor, 140 amperes; speed of motor, 750 revolutions per minute; pulley diameter, 21 inches; belt tension, tight side, 950 pounds; slack side, 350 pounds.

398. Compute the commercial efficiency of the generator given in Questions **386** and **392**, including the loss in belting, if it is driven by a vertical belt. Use the average of the respective percentages given in Table **30**, Instruction Book.

PART II.

Design of Alternating Generators and Synchronous Motors

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PART II.

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SYMBOLS USED IN ALTERNATOR DESIGN.

In this Book on *The Design of Alternating Generators and Synchronous Motors,* the symbols here given are used in the following significations. It must be remembered, that the symbols and their respective significations are not standard, but have met with general approval and acceptance.

$\bar{A}_1$ = Field ampere turns.
A_{1s} = Field ampere turns corresponding to the normal armature back ampere turns on short circuit.
A_2 = Normal armature back ampere turns.
a = Pole arc.
B_a = Magnetic density in armature core.
B_p = Magnetic density in pole core.
B_r = Magnetic density in wheel rim.
B_t = Magnetic density in teeth.
C = Armature phase current.
C_l = Line current.
C_1 = Current in the field winding.
C_p = Phase current.
c = Pole shoe height.
D = Internal diameter of the armature.
D_1 = External diameter of the magnet wheel.
D_2 = External diameter of the armature.
d = Pole core height.
δ = Value of air gap.
E_l = Line voltage.
E = E. M. F. on the armature phase winding.
E_p = Phase voltage.

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e = Voltage on the field terminals.
η = Efficiency.
F_1 = Flux in the field system.
F_2 = Flux in the armature system.
f = Length of the pole core.
f_1 = Size factor or output coefficient.
g = Length of the wheel rim.
h = Height of the wheel rim.
i = Slot depth.
k = Armature core height.
k_s = Short circuit constant.
$KVA.$ = Kilovolt amperes.
$K.W.$ = Kilowatts.
l = Length of the armature core.
l_1 = Projecting out part of the winding.
L_2 = Length of mean armature turn.
L_1 = Length of mean field turn.
λ = Number of ventilating ducts.
$M.\ M.\ F.$ = Magnetomotive force.
m = Number of phases.
μ = Permeability.
N = Number of revolutions per minute.
n = Number of cycles, periodicity or frequency.
o = Slot pitch.
O_1 = Cooling surface of the field coils.
O_2 = Cooling surface of the armature.
p = Number of pole pairs.
q_2 = Sectional area of armature conductor.
q_1 = Sectional area of field conductor.
r = Tooth thickness.
r_0 = Air gap reluctance.
$r_1{}^1$ = Reluctance of field leakage path.
$r_2{}^1$ = Reluctance of armature leakage path.
R_1 = Total resistance of field coils.
R_2 = Total armature resistance.
σ = Leakage factor.

S = Total number of slots.
τ = Pole pitch.
T_1 = Temperature rise in field coils.
T_2 = Temperature rise in the armature.
$\cos \varphi$ = Power factor.
w_h = Hysteresis loss in watts per lb. of iron.
w_e = Eddy current loss in watts per lb. of iron.
W_a = Watt losses in armature winding (copper losses).
W_c = Watt losses in armature core (iron losses).
W_t = Watt losses in the teeth (iron losses).
W_m = Watt losses in the field winding (copper losses).
W_f = Watt losses due to friction and ventilation.
V = Peripheral speed.
Z = Number of conductors per armature phase.
z = Number of turns per pole.
ω = Specific resistance of copper.

NOTE.—The numerical calculations in this Book have in nearly all cases been carried out by means of the *slide rule.* Students should, therefore, make due allowance for slight apparent discrepancies in the results of calculations given in the Book.

CONVERSION TABLE OF ENGLISH UNITS TO METRIC UNITS.

Measures of Length:

1 inch = 2.54 centimeters.
1 foot = 30.48 “

Measures of Surface:

1 square inch = 6.45 square centimeters.
1 “ foot = 929 “ “

Measures of Capacity:

1 cubic inch = 16.38 cubic centimeters,
1 “ foot = 28316 “ “

Measures of Weight:

1 pound = 0.453 kilogram.
1 hundredweight = 50.8 kilograms.
1 ton, 2240 lbs., = 1016.04 kilograms.

Measures of Temperature:

9 degrees Fahrenheit = 5 degrees C.
Temperature Fahrenheit = $\frac{9}{5}C^\circ + 32$.

VARIOUS CONSTANTS.

Weight of Materials:

Copper weighs 0.32 lb. per cubic inch; or 8.86 kg. per cubic decimeter.

Wrought iron weighs 0.28 lb. per cubic inch; or 7.75 kg. per cubic decimeter.

Specific Ohmic Resistance of Copper:

At a temperature of 135°F. = 57°C.:
$8/10^7$ ohm for 1 inch length and 1 square inch section;
0.02 " " 1 meter " " 1 " millimeter section.

Peripheral Speed:

1,000 feet per minute = 5.08 meter per second.

Specific Pressure:

1 lb. per square inch = 0.07 kg. per square centimeter.

Power and Energy Units:

1 English horsepower = 746 watts.
1 Metric " = 736 "
1 foot pound = 0.138 kilogrammeter.

THE DESIGN OF ALTERNATING GENERATORS AND SYNCHRONOUS MOTORS.

1. **Duties of the Designer.**—The duty of the designer is to provide in his design all the desirable elements of an alternator for the minimum manufacturing cost. The work of a designer seldom exceeds the calculation of magnetic and electrical data of the machine. For the mechanical design he has the assistance of the drawing office staff; the workshop staff looks after the manufacturing, and, finally, the checking of the design is carried out in the test room. The satisfactory and economical work of all these departments is based on the requirements of the machine designer; therefore, he must be conversant with mechanical construction, the general workshop methods of economical production and be able to read the test data and make his deductions therefrom. With further experience and knowledge obtained from past designs he will be able to meet all the requirements of machinery users as well as the manufacturer.

2. **Types of Alternators.**—Alternating current practice has developed two classes of alternators, namely: (1) the *separately excited alternator*, which was until recently in exclusive use; and (2) the *self excited alternator*, which has been brought out recently.

The separately excited generator receives its magnetizing current from a continuous current supply, which in most cases is an exciter directly coupled to the generator or driven by an external source. The excitation voltage seldom exceeds 250 volts.

Fig. 1 indicates the connection diagram of a separately excited alternator.

3. Separately Excited Alternators.—The main field circuit is connected in the following manner. The two ends of the magnet coils *B* of the alternator *A*, Fig. 1, are connected to slip rings *C*, which receive the magnetizing current through brushes connected to the terminals of the exciter *D*. Generally, the alternator field circuit contains a regulating resistance R_1, in order that the excitation current may be varied, so as to obtain a constant pressure under varying loads at the generator terminals.

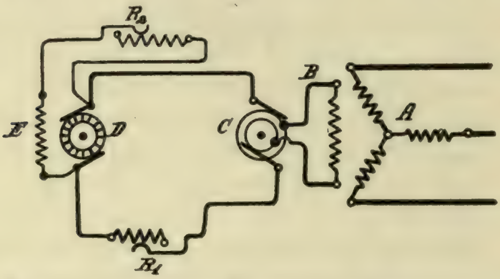


FIG. 1.—CONNECTION DIAGRAM OF SEPARATELY EXCITED ALTERNATOR.

For fine adjustment of the excitation, a second regulating resistance R_2 is placed in the exciter field circuit *E*.

4. Self Excited Alternators.—The self excited generator requires no exciter, the current being taken directly from the alternator terminals, after passing through a suitable number of brushes, to a commutator *C*, Fig. 2. This commutator, of special design, takes the place of the slip rings, and its segments are connected to the circuits of the magnet winding *B*.

As the voltage of the excitation current should not exceed about 50 volts, a pressure transformer T_1 T_2 is often applied, as indicated in Fig. 2, which gives the connections of a self excited generator.

5. The Classification of Alternators.—The arrangement of the armature and field system leads to a further classification of alternators, namely: (1) *Revolving Armature* type; (2) *Inductor* type; and (3) *Revolving Field* type.

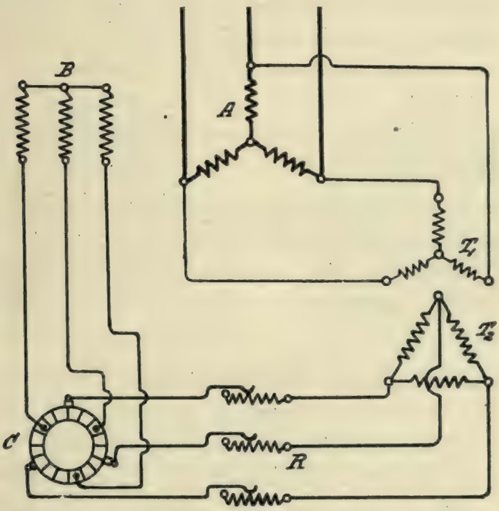


FIG. 2.—CONNECTION DIAGRAM OF SELF EXCITED ALTERNATOR.

6. Revolving Armature Alternator.—The revolving armature alternator has been developed from the continuous current dynamo; slip rings which are two, three or four in number, according to the number of phases, replace the commutator.

To obtain a single phase current, the closed armature winding is tapped at two points, which are 180 degrees apart on its circumference; for a two phase current, at four points, with a displacement of 90 degrees to each other; and for a three phase current at three points 120 degrees apart.

7. **Limit of Use.**—The use of this type of generator is limited to low voltages and comparatively low speeds, and in cases where it is directly connected with a prime mover, in which a flywheel effect is not necessary in the revolving part of the generator.

For high voltage machines, the *insulation* of the coils is one of the leading features of design. It is inherent to the nature of good insulation, that it cannot be subjected to mechanical stresses of any importance. This difficulty is evidently overcome in the easiest and most reliable way, by making the armature stationary, as is the case in the other types.

The revolving armature is only applied to low voltage and medium speed generators of, say, up to 100 K. W. This principle is also largely applied to rotary converters of various sizes.

8. **Inductor Type Alternator.**—The principal feature of the inductor alternator is the entire absence of any revolving winding and sliding contacts, as both excitation and armature terminals are fixed on the iron frame. A single stationary coil provides the necessary magnetomotive force for the magnetic circuit of the machine.

The magnet wheel of cast iron, or the cast steel spider with the necessary number of pole projections, is generally fitted with laminated pole shoes.

The armature frame is made of cast iron of ample cross section, to guard against any sag due to the weight or magnetic pull. This frame carries the field iron stampings, which form the magnetic path. Slots are stamped out on the inner periphery of the sheet iron, to take the armature coils.

9. **Limit of Use.**—This type of machine has not been used to any great extent, on account of the electrical and magnetic disadvantages, due to the high leakage coefficient of the magnet system. This loss, however, can be greatly decreased in high speed generators by reducing the number of poles. Besides mechanical advantages, the inductor type alternator gives somewhat better efficiency than the other types and its application can be recommended for small outputs, high speeds and low frequencies.

Fig. 3 gives the general arrangement of an inductor generator in cross section and side view.

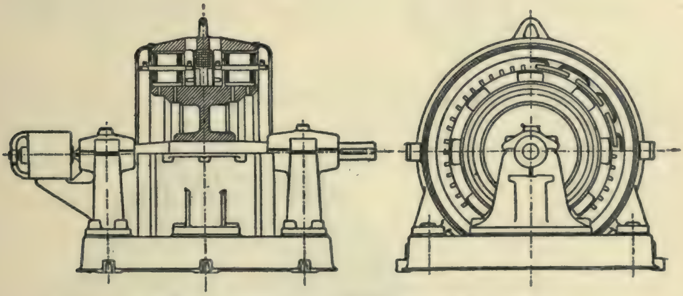


FIG. 3.—INDUCTOR TYPE ALTERNATOR.

10. **Revolving Field Alternator.**—The revolving field type machine is characterized by having a stationary armature and a revolving magnet wheel, to which the poles are attached by means of strong bolts or similar attachments.

Fig. 4 represents a revolving field type generator in cross section and side view; Fig. 4*A* shows a similar type of machine in perspective. This class of alternator is seldom built for smaller outputs than, say, 10 K. W., because, for smaller outputs this type presents mechanical and commercial difficulties in finding room for the field coils.

11. **Limit of Use.**—The revolving field generator is especially suitable for heavy work and high voltages in connection with any kind of prime mover, but its real value will be

appreciated when several alternators are working in parallel.

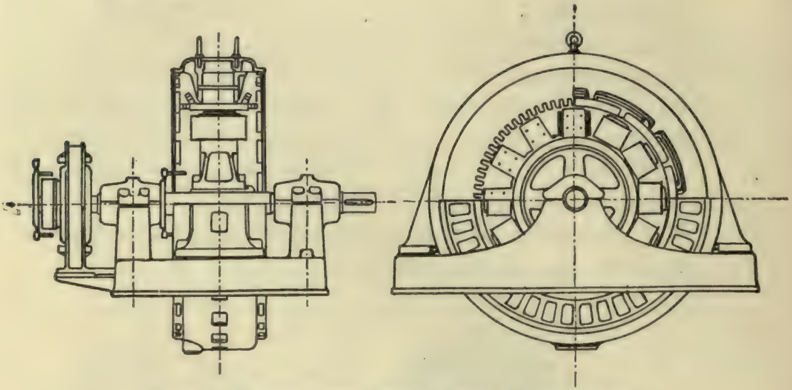


FIG. 4.—REVOLVING FIELD TYPE ALTERNATOR.

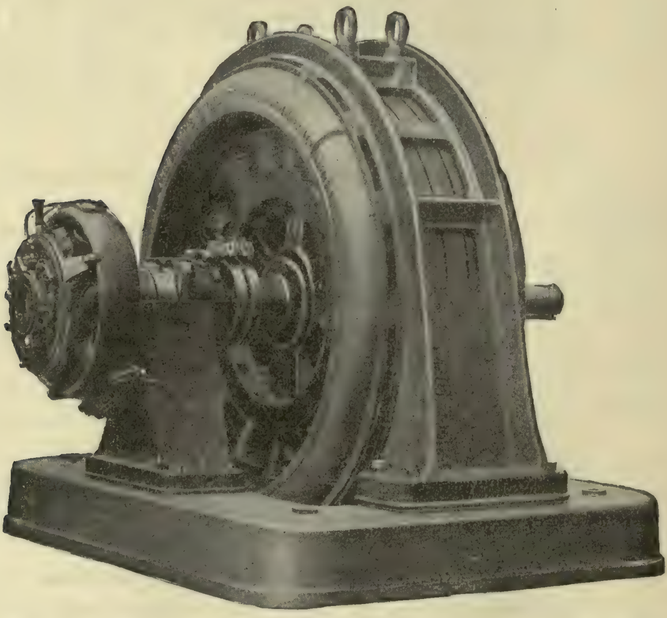


FIG. 4A.—REVOLVING FIELD TYPE ALTERNATOR WITH DIRECT CONNECTED EXCITER.

If necessary, the field magnet wheel can essentially contribute to the flywheel power of the combined engine and alternator set in connection with steam engines, gas engines or other prime movers. The revolving field type machine is almost universally adopted in modern practice.

12. Characteristics and Efficiencies.—Reasonable working conditions of an alternator only will enable the manufacturer to turn out a good commercial machine, which will satisfy the station engineer. These conditions have been arrived at through recent experience, and for standard alternators they can be termed as follows.

13. Commercial Efficiencies.—Table 1 indicates the commercial efficiencies of different sizes of polyphase generators for full and half loads.

TABLE 1.–EFFICIENCIES OF POLYPHASE ALTERNATORS.

Output of Alternator.	Average Commercial Efficiency.	
	At Full Load,	At Half Load.
5 KVA.	.85	.80
10 "	.86	.82
5 "	.88	.84
50 "	.90	.85
100 "	.91	.86
200 "	.92	.87
300 "	.93	.88
500 "	.94	.90
750 "	.95	.91
1,000 "	.96	.92

The efficiencies of single phase machines given in Table 2, are slightly lower than those of the corresponding polyphase generators.

TABLE 2.—EFFICIENCIES OF SINGLE PHASE ALTERNATORS.

Output of Alternator.	Average Commercial Efficiency.	
	At Full Load.	At Half Load.
5 KVA.	.83	.75
10 "	.85	.80
25 "	.86	.81
50 "	.88	.82
100 "	.89	.83
200 "	.90	.84
300 "	.91	.85
500 "	.93	.87
750 "	.94	.89
1,000 "	.95	.91

14. Voltage Drop.—The voltage drop on alternators at full load should be, on an average, about

7%, with a power factor, $\cos \varphi = 1.0$;
22%, with a power factor, $\cos \varphi = 0.8$;
26%, with a power factor, $\cos \varphi = 0.6$.

This is shown graphically in Fig. 5, curve *B*.

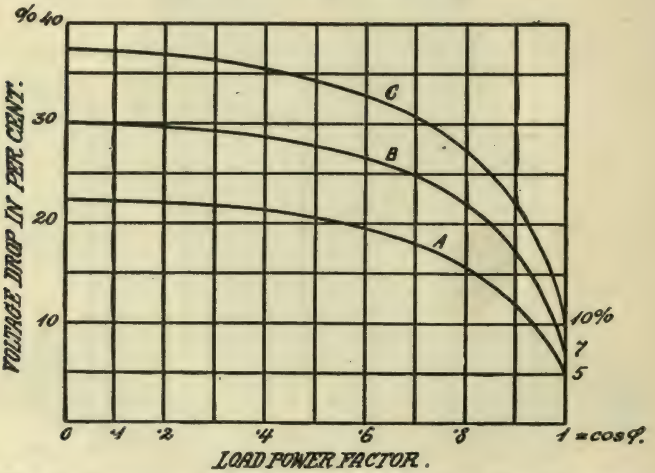


FIG. 5.—AVERAGE VALUES OF VOLTAGE DROP FOR DIFFERENT POWER FACTORS.

The voltage drop is specified as the alteration or decrease, as the case may be, of the armature pressure, when the full load is switched on the fully excited generator, speed and excitation remaining constant.

15. **Slots Per Pole.**—To procure a practically sinusoidal wave form of the current, the application of six slots per pole will be found a good average figure.

16. **Temperature Rise.**—The average rise of temperature above that of the surrounding air, of any part of the machine, should not exceed the following values after a run of six hours at full load: The armature winding, 75°F. rise; the field coils, 65°F. rise. On all other parts of the machine, the permissible temperature rise is 75°F., all temperatures to be measured by means of a thermometer.

17. **Short Circuit Current.**—The alternator should not have a greater short circuit current than about three times the normal current, when the excitation corresponds to the normal open circuit voltage for the normal speed. For the definition of short circuit current see Pars. **117** and **118**.

18. **Insulation Test.**—The insulation of the armature coils should be able to withstand double the normal voltage, and the field coils five times the normal voltage, for five minutes.

19. **Space.**—As regards mechanical features, the generator should take up as small a space as possible, the construction should be rigid and must offer every facility for repairs and give assurance against accident.

20. **Effect of Altering the Design.**—Supposing that the design of a generator is in every respect satisfactory and

is also in accordance with a certain specification, any departure from the above mentioned conditions in one or the other way has the following effects:

21. Increase of Efficiency.—A higher efficiency than that stated in Tables **1** and **2** offers to the station engineer a generator which is more economical in working, but it necessitates the manufacturer producing a more expensive machine. Taking into consideration a perfect design, an inexpensive increase in efficiency can only be obtained by the choice of good material for the iron core and copper winding. For the different items of efficiency calculation see Par. **78**.

22. Decreased Voltage Drop.—A smaller voltage drop than that given in Par. **14** seems a desirable feature to the station engineer, as it insures better regulation on the light and power circuit and reduces the attendant's work, but on the other hand a lower voltage drop may cause trouble when alternators are running in parallel, or when a short circuit accidentally occurs. The manufacturer, in order to produce any decrease of the voltage drop, has to increase the weight of material in the machine, which of course increases the cost of the generator.

23. Increase of Slots.—The experience of the station engineer has generally proved, that it is most advantageous to have a generator with an E. M. F. of a nearly sinusoidal wave form. It helps the parallel running of alternators, the switching of same on the circuit and improves the running of motors from a circuit so supplied. The more armature slots a generator has, the nearer will be the wave form of the E. M. F. to the sine curve, but this advantage can be obtained only at an increase in manufacturing cost.

A generator with many slots will be larger than one with a smaller number, because: (1) the value of the E. M. F. factor is in *inverse relation* to the number of slots; (2) an increased number of slots means the application of more insulation material, thus a loss of winding space; and (3) it implies the use of several sizes and forms of coils which necessitate the manufacture and stocking of different sizes of formers.

24. **Decreased Temperature Rise.**—The specifications of the permissible temperature rise, insures the long life of the machine and prevention of break downs originated by excessive heating. The necessary data is based on the quality of insulation materials used in modern practice. The station engineer prefers, of course, to take a machine with a temperature rise as low as possible, consistent with the price, which of course means a larger alternator. This, from the manufacturer's point of view, is unreasonable, especially when all modern means of cooling and ventilation have been applied in the construction of the properly designed machine.

25. **Increased Short Circuit Current.**—A greater short circuit current than *three* times the normal is usually considered an unnecessary evil, because, as already mentioned, it may injure the generator.

First of all, in case of an accidental short circuit, the excessive current may burn out the armature winding, which is naturally dimensioned for the normal current only. Secondly, it will cause the occurrence of heavy *surging currents* through the armatures of alternators running in parallel.

A generator with a large short circuit current is expensive and demands the use of an excessive amount of field copper.

26. **Increased Insulation.**—A higher safety factor of insulation to withstand a test greater than that given in Par.

18, means the waste of precious winding space, which would be taken up by unnecessary insulation material.

The greater the space, in percentage of the whole machine body, occupied by the active material, the more efficient and economical will be the machine.

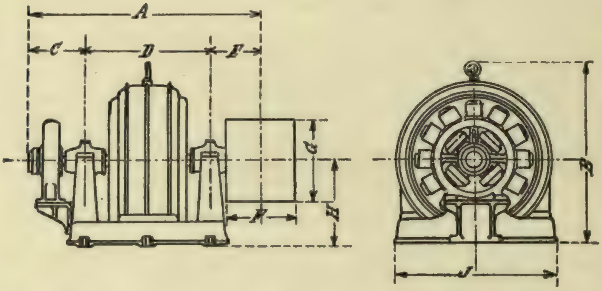


Fig. 6.—Revolving Field Type, 50 Cycle, Polyphase Alternator of European Design. (See Table 3.)

TABLE 3.—DIMENSIONS OF REVOLVING FIELD TYPE, 50 CYCLES, POLYPHASE ALTERNATORS. (SEE FIG. 6.)

KVA.	R.P.M.	Weight in Lbs.	A	B	C	D	E	F	G	H	J
45	1,000	4,000	62½″	39½″	17¾″	34½″	9¾′	12½″	18″	16″	34″
60	750	4,800	65½	44½	17¾	37¾	11	14	18	18	40
80	750	5,400	68¼	44½	18¼	38	12	16	19½	18	40
150	600	8,100	78	59½	19½	42½	16	21½	25	25½	53
200	500	11,000	82	59½	21	44	17	23½	27½	25½	53
275	430	14,900	99	79	22½	54½	22	—	—	37½	73
350	430	19,100	99	79	22½	54½	22	—	—	37½	73
550	375	28,200	—	91	—	60	—	—	—	—	—
780	300	47,200	—	123	—	67	—	—	—	—	—

27. Dimensions of Generators.—For general guidance, the accompanying Tables, *3*, *3a* and *4*, when applied to Figs. 6, 6*a* and 7 respectively, will give the overall dimensions of two lines of machines, one of European (Continental) and the other of English-American make.

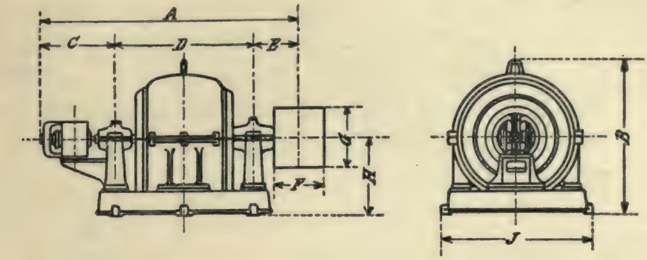


FIG. 6A.—INDUCTOR TYPE, 50 CYCLE, POLYPHASE ALTERNATOR OF EUROPEAN DESIGN. (See Table 3a.)

TABLE 3a.—DIMENSIONS OF INDUCTOR TYPE, 50 CYCLES, POLYPHASE ALTERNATORS. (SEE FIG. 6a.)

KVA.	R.P.M.	Weight in Lbs.	A	B	C	D	E	F	G	H	J
45	1,000	4,850	65″	43″	21″	34″	10″	11½″	15½″	18¼″	40″
65	1,000	6,400	78	45½	22	45	11	12½	15½	20¾	40
100	750	9,300	89	52	26¼	49	13½	14	19½	22½	53
130	600	14,100	98	60	28¼	53	16¾	19½	23½	26	55
200	600	17,600	104	60½	30¾	56	17¼	21½	23½	26½	61½
275	600	21,800	115	67	31¼	61	22¾	—	—	33½	61½
325	500	31,100	117½	81½	31¼	63½	22¾	—	—	38½	62½
550	375	52,800	150	93	33	86½	30½	—	—	41½	—
800	300	84,700	156	98	36¼	86½	33½	—	—	44	—

28. Choice of Materials.—The first consideration of the designer has to be directed toward the choice of the different materials, and, secondly, to the constructional details with regard to manufacturing expenses, repairs, interchangeability facilities, erection and transportation conditions.

In the following paragraphs the different parts of a *revolving field* type alternator will be discussed.

THE ARMATURE.

29. The Armature.—The armature of a high speed or medium speed generator of average size has comparatively moderate dimensions, and a cast iron frame or carcase of ample cross section has the necessary rigidity in itself to bear its own and the weight of the armature core, so withstanding any possible one-sided magnetic pull, due to an eccentric position of the magnet wheel inside the stationary armature.

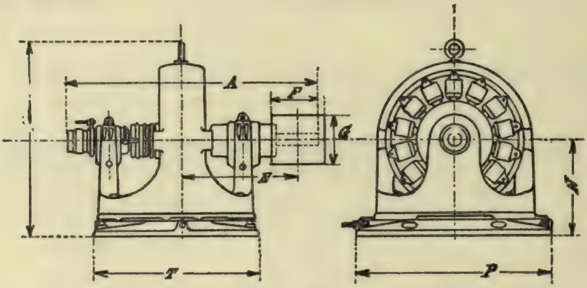


Fig. 7.—Revolving Armature Type, 60 Cycle, Polyphase Alternator of English-American Design. (See Table 4.)

TABLE 4.—DIMENSIONS OF REVOLVING ARMATURE TYPE, 60 CYCLES, POLYPHASE ALTERNATORS. (SEE FIG. 7.)

KVA.	R.P M.	Weight in Lbs.	A	E	F	G	M	N	P	T
50	900	4,100	$70\frac{11}{16}''$	29¼″	12″	18″	46½″	23½″	46¾″	18″
75	720	7,600	$82\frac{9}{16}$	36¼	15	25	55⅛	27¾	55	25
120	720	10,600	91½	40½	17	25	65½	34	64½	25
180	515	13,800	100¾	42¼	25	35	71¾	35	72	35
250	450	22,750	155	53½	38	40	85¾	46	98	40
400	400	41.000	162	58½	50	45	109½	54	113	45
600	327	62,000	168½	61½	46	60	134	72	142	60
750	327	82,000	190	70½	66	60	147	79½	142	60

For an overall diameter not exceeding five feet, the cast iron frame is preferably cast in one piece and is provided with the necessary ventilating holes.

Armature frames with an overall diameter of above five feet are divided in two, four or more parts, according to the size, and are usually of box section, as shown in Fig. 8.

For very large generators, the question of transportation and packing as well as that of erection has specially to be taken into account, and accordingly the overall dimensions of the largest part, or the weight of the heaviest piece, will be in many cases limited, and such limits have therefore to be carefully considered by the designer.

30. Method of Building.—Experience has shown that heavy castings are liable to alter their shape if machined in any other position than the final one. For upright machines, the frame is turned in a vertical position and all necessary care must be taken to avoid any alteration of the true shape of the armature. If the shape is not true a magnetic pull will take place due to the eccentricity.

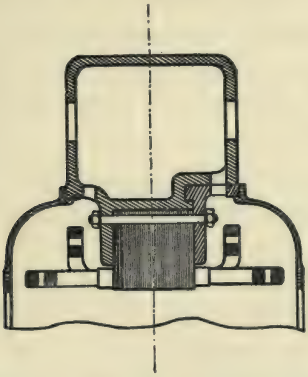


FIG. 8.—SECTIONAL VIEW OF ARMATURE FRAME FOR LARGE ALTERNATORS.

In placing the sheet stampings of the core into the cast iron frame of the armature, care must be taken that the latter is clamped down on an accurate floor plate, until the core is ready to receive the coils. This method prevents the armature from altering its true shape under the effect of the bolts which compress the core plates together.

The stampings are of soft sheet iron or steel of the highest permeability, the choice of this material having an important influence on the efficiency. The plates are about

0.02 inch in thickness and each sheet is insulated from its neighbor by paper or varnish, so as to minimize the eddy current losses.

31. Windings.—The slots or holes on the inner periphery of the iron take the armature coils, which in case of open slots are wound on a wooden former to template, so as to insure interchangeability.

In winding the coils each layer is covered with varnish; afterwards they are thoroughly dried to expel all moisture, in order to prevent any internal breakdown in the coil. This drying process can be advantageously performed by applying the short circuit current for a few minutes, and repeating the performance several times.

The coils are held in place by means of wooden or fibre wedges.

32. The Core.—The armature core is generally built up of sheet iron, 0.01 to 0.02 inch in thickness, insulated with paper or varnish.

The most reliable insulation material is paper of about 0.002 inch in thickness, which can be cut in proper disc or segment form and stuck to the sheet iron, this work can be performed by means of a special machine. The proportion of the *effective* iron volume to the *total* volume of the armature core is about .85 to .90.

33. Method of Building.—In building the armature core, special care has to be taken in providing solid cheeks or end plates. In order to do this, stampings having a thickness of 0.1 inch are placed on the cheeks of the iron core, so as to give solidity to it, thus preventing the teeth of the thin sheet iron stampings from bending over under the pressure of the clamp rings or bolts.

It should not be possible to drive the edge of a knife or finder between the stampings of a finished armature.

The inner surface of the armature core need not be machined, because with proper care taken in stamping and piling the core sheets, a true smooth surface can be obtained.

Regarding iron losses, it is an advantage not to have the inner periphery machined.

Stampings of a diameter less than two feet can be made in one disc, but for larger sizes *segments* are used which are piled overlapping. As a rule the greater the number of segments used to form a complete ring, the better, as assembling is more difficult with large segments.

34. Ventilation and Air Ducts of Armature Core.—To obtain a uniform temperature throughout the armature, as well as good ventilation, it has proved economical to use an air duct about every three to four inches, parallel to the laminations. These air ducts should not be less than, say, ½ inch wide. The distance pieces should be so arranged as to provide free access for the air passing through the ducts.

Thick iron end plates are applied in the ducts, to support the thin stampings, in a manner similar to that of the two outside cheeks, see Par. **33**.

In cooling an armature core with ventilating ducts, special care is required in order to keep the stampings in proper shape and not to distort the slots.

In all cases it is advisable to note, that the winding space of the assembled armature core is less than that of a single slot of a stamping, but an additional 0.03 inch will make up for this difference. This point requires particular attention, because a tight slot may cause considerable trouble and increase of labor, so that all advantages of the economy in winding space are soon made illusory.

35. Clamping and Piling.—It is a matter of importance, that the armature core should be piled up with exclusive regard to the slots for the coils. The bolts used to hold the armature core during the piling and pressing should be somewhat smaller in size than the holes, but after this operation is completed, each bolt is replaced by another bolt which fits its hole tightly. The holes should be reamed out to provide for a tight fitting bolt.

In the case of an armature divided into several parts, a perfect joint is essential between the adjoining surfaces of the armature core, and the designer should be careful to take into account the magnetic resistance between these core joints. The number of segments must be in accordance with the number of slots, as well as the number of partitions or ducts. If necessary, half segments can be applied in the design next to the joints.

36. Form and Number of Slots.—The form and number of armature slots has not only an influence on the working or performance of the generator, but influences the choice of the insulating material, as well as that of the magnet poles. Generally, from the standpoint of electrical design, shallow and broad slots are favored, as they give smaller leakage, but for mechanical reasons the teeth should never be less than 0.1 inch in width.

The teeth must be kept tight by the thick end plates on the side faces, in order that they should not work loose and cause *humming*. Generally speaking, the ratio between the *depth* and *width* of a slot should not exceed 3.

The use of a closed or half closed hole implies the use of hand wound coils, or in low tension work, the application of copper bars. The application of closed holes means an increase in the cost of winding; but on the other hand it permits the employment of solid pole pieces, which is a great advantage, as explained in Par. **47**.

37. Open Slots.—With open slots the armature coils may be machine wound, better insulated and easily exchanged.

For high tension alternators it is advisable to use open slots only and so far general practice approves the use of the open slot for all cases.

The section of copper conductors and the choice of form is an important item, because upon it depends the economical utilization of the winding space inside the slot.

In works where standard stampings with certain slots are stocked, the designer is very often compelled to arrange the copper wires according to the slot form. It is often found advantageous to use two, three or more wires in parallel, instead of a single thick wire, in order to fill the slot neatly.

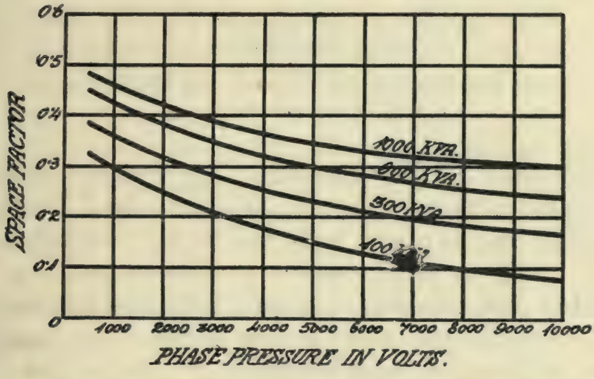


FIG. 9.—AVERAGE SLOT SPACE FACTOR FOR FOUR DIFFERENT SIZES OF ALTERNATORS.

38. Space Factor.—Fig. 9 gives the average values of space factor for different voltages and sizes of machines. The space factor is defined as the *ratio* between the *copper section inside the slot* and the *air section of the slot.*

39. Shape of Conductors.—For large current machines, the following conditions are to be taken into consideration in choosing the armature conductors. A conductor of large section is liable to produce eddy currents which decrease the efficiency; therefore it is better to use several *parallel connected* conductors. For this purpose special cables are very useful, as they can be pressed into the proper shape suitable for the slot. For high tension machines round wires are the most suitable.

40. Insulation.—In alternating current designs where the pressure ranges from the smallest value up to 20,000 volts or more, the question of insulation becomes a most important one. To secure good insulation between the armature winding and the iron core, the coils are placed in the slots covered with a certain quantity and quality of insulating material according to the voltage of the machine, and the whole is again held in a fixed position by means of fibre or wood wedges, which prevent the coils from shifting.

41. Quality of Insulation.—The material placed between the coils and iron core must have the following qualities:

(*a*) Uniform and high insulating qualities, so that the thickness can be reduced to a minimum.

(*b*) The variation in quality with the temperature to be a minimum, so that the temperature of the machine may be driven as high as possible.

(*c*) It should not be affected by any mechanical treatment, but possess a high mechanical quality; for instance, it should be possible to bend it on a small curve without losing its good properties.

(*d*) The material should not be hygroscopic, but able to stand damp as well as dry air.

42. Mica.—The insulating qualities of mica have proved to be the best, but it has very little mechanical strength and is extremely brittle besides being expensive.

For medium as well as for high tension machines, the usual material adopted is *micanite,* a flexible material which is made up of small sheets of mica pasted, pressed and baked together, with as little varnish as possible. The curves, Fig. 10, indicate the different thicknesses of micanite tubes and oil cloth required for different working pressures.

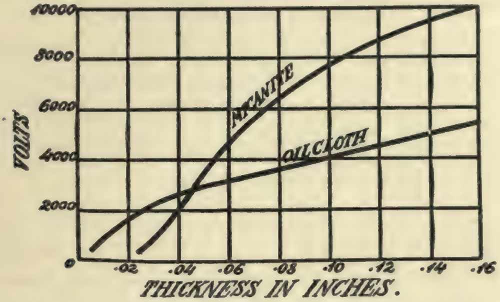


FIG. 10.—AVERAGE THICKNESSES OF SLOT INSULATION FOR DIFFERENT VOLTAGES.

In laying out the curves of Fig. 10, the bending and pressing of the material inside the slot is allowed for and they give full safety against a testing pressure double that of the normal.

43. Other Materials.—Oil cloth, specially prepared for alternating current work, is a most suitable material for medium pressure, and it may be used together with press-board, or for high tension work with micanite. Press-board has very good mechanical qualities; it can be bent over curves of the smallest radius and its insulating quality against puncture is a good one, see Table **5**. Fibre is a

TABLE 5.—SAFE THICKNESSES OF PRESS-BOARD FOR DIFFERENT PRESSURES.

Thickness in Inches.	Pressure in Volts.	Thickness in Inches.	Pressure in Volts.
.01	125	.06	2,858
.02	400	.07	3,650
.03	900	.08	4,500
.04	1.500	.09	5,500
.05	2,100	.10	6,500

good insulating material, but cannot stand medium or high temperature, as it becomes soft at about 180 degrees Fahr.

44. Insulation of Coils.—The coils when projecting out of the armature are wound in such a manner as to prevent a breakdown between any coil of one phase and any coil of another, or between any coil of any phase and the frame of the machine. For the first purpose, safe distances are to be kept between the end connections of the coils, which are taped over and varnished.

In high tension machines it is essential to have a safe distance between the live copper and the iron. As an additional safeguard it is well to cover the iron opposite the coils with cloth and varnish, for example, in a 6,000 volt machine a distance of about 2 inches between any two coils of two different phases and 2.5 inches between the well insulated copper windings and cloth covered iron, is to be provided.

45. Insulation of Armature Conductors.—The proper insulation of the armature conductors also requires careful attention on part of the designer. It is best to cover conductors of large section with oil linen, which can be done on ordinary taping machines. For wires used in medium or high pressure machines the insulation material adopted is cotton. For medium pressures the conductor receives a double or single covering and one braiding. Table **6** indicates the usual thicknesses of double covering and braiding as used for low tension work.

TABLE 6.—INSULATION THICKNESSES OF ROUND WIRES AS USED FOR LOW TENSION.

Double Cotton Covering.	One Cotton Covering and One Braiding.
.008 inch.	.027 inch.
.010 "	.030 "
.012 "	.032 "
.015 "	

For high tension, the triple covering of thicknesses as per Table 7 has been found sufficient.

TABLE 7.—INSULATION THICKNESSES OF ROUND WIRES AS USED FOR HIGH TENSION.

Triple Cotton Covering.	Double Cotton Covering and One Braiding.
.012 inch.	.027 inch.
.015 "	.030 "
.020 "	.033 "
.028 "	.036 "

46. Arrangement of Conductors.—The arrangement of wires inside the slots is a matter of importance, and the proper arrangement and succession of the turns will add much to the safety *against breakdown.* Fig. 11 shows a slot with its high tension winding. The armature coil has been formed on a mould, taped over with cloth, 0.008 inch in thickness and placed inside the slots, which are insulated from the armature coil by suitable material.

In modern practice it is required that any defective coil may readily be taken out and replaced by a sound coil; that a defective coil can be temporarily cut out of circuit and bridged over until repairs are possible; that any shifting of the coils shall be practically impossible, and that the potential difference between any two neighboring coils of different phase shall be reduced to a minimum.

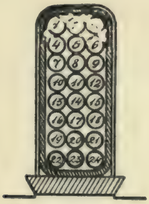


FIG. 11.—SLOT WINDING OF EXTRA HIGH TENSION ALTERNATOR.

THE MAGNET SYSTEM.

47. The Magnet System.—The magnet wheel consists of a cast iron or cast steel spider, with the pole pieces which are of solid steel all through, or with a solid magnet core but laminated pole shoes, or of laminated sheet iron all through.

Cast steel poles can be used in connection with closed or half open slots, but laminated pole shoes are to be applied with an armature of open slots in order to reduce the eddy currents and losses in the pole faces. The thickness of the lamination should be 0.04 inch and between the sheets some good insulating varnish or the oxide insulation of the plate itself is sufficient.

The ratio between the effective iron section and the total iron section is about 0.95.

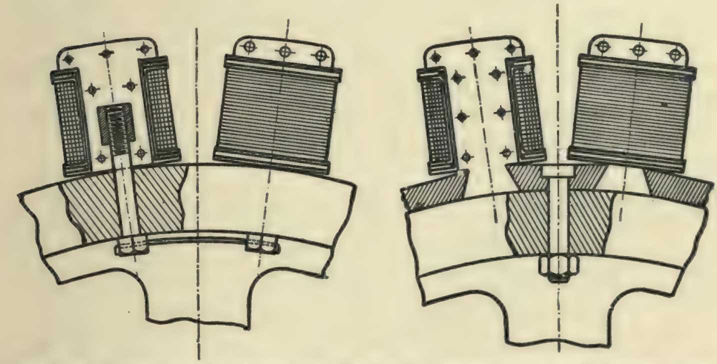
48. Solid Poles.—Generally speaking the cost of manufacture of solid cast poles or laminated ones is about the same. The advantage resulting from the application of solid pole pieces, consists in the damping effect of the same, so improving the parallel working of the alternators; and, further, that for high speed machines, the fixing of the solid pole pieces is more reliable, as strong bolts may be used.

Another advantage of the solid pole piece, is that the section can be made oval or circular, so reducing the leakage of the field system. The amount of field copper is also reduced, as the peripheral length is less for a certain cross section of oval form than the length for the same cross section of rectangular form. By the use of an oval section in certain designs the economy in copper is sometimes considerable.

49. Laminated Poles.—With laminated pole pieces, the magnet wheel is more certain to run true and to keep its shape; also the designer is more likely to perfect the design as regards shape, pitch and quality.

The fixing of the magnet limbs on the wheel rim is a constructional detail which must be carefully considered by the designer. Figs. 12 and 13 show two methods of fixing the magnet limbs on the wheel rim.

On very large machines it is advisable to give the laminated magnet limbs the same rigidity and stability as that of the solid cast steel type. This can be attained by welding the surfaces which are not exposed to induction effects by any electrical method.



FIGS. 12 AND 13.—METHODS OF FIXING POLE PIECES ON REVOLVING FIELD TYPE ALTERNATORS.

50. Magnet Wheels.—For large generators with magnet wheels over four feet, the wheel should be cast in two or more parts, so as to avoid internal stress in the material. The different parts of the magnet wheel are connected together by means of bolts and shrinking rings.

For magnet wheels of about four feet, the splitting of the magnet wheel hub is sufficient to take up the internal stress, providing that the magnet rim is not too heavy, in order to obtain a flywheel effect in the generator.

51. Cyclical Variation.—In the case of direct coupled alternators working in parallel, there are two alternatives to secure the necessary minimum cyclical variation. Either the ordinary engine flywheel can be retained and the alternator magnet wheel placed side by side with the flywheel, or a part of the rotating weight is put in the alternator wheel to obtain the total amount of flywheel effect. The latter arrangement is the most economical and requires less space.

Direct coupled alternators, for low, medium and high speeds, are usually of the *flywheel type* with a revolving magnet wheel. It is necessary to make the diameter of the alternator of ample dimensions, to allow the application and arrangement of the necessary revolving mass, which should be placed as near as possible to the periphery.

52. Periodicity.—As will be seen from practical examples, large flywheel generators are specially suitable for 50 and higher periodicity. It will be found difficult to design an economical high or medium speed alternator for 25 cycles, because the most favorable diameter would not permit the arrangement of rotating flywheel mass.

53. Knowledge of Workshop Methods.—In order that the designer shall arrive at the best design as regards economy in manufacture, he must be able to calculate the labor costs on different parts of the machine; therefore he must be aware of the different workshop methods, especially if they are out of the standard, as is the case with large generators. For standard machines, the designer has generally data and empirical rules for calculating the material, as well as the labor costs.

With reference to the method of machining the magnet wheel of a heavy alternator, it should be noted that the hub is first bored and faced on a powerful horizontal boring and milling machine; afterwards the wheel is clamped on a shaft which is run over a pit and is completed in this position without taking it from the shaft. This method of machining and building results in the perfectly true running of all parts of the wheel.

54. **Field Coils.**—The field coils of smaller sizes are generally wound with double cotton covered copper wire and those of larger sizes are preferably wound with copper strip on edge, the turns being insulated from each other with paper or micanite.

The insulation between the coils and the pole core is in most cases press-board or paper, which has very good mechanical qualities, for such are required on the revolving part of a generator. The coils being former wound and interchangeable are held in position by means of the extension of the pole pieces, the coil can be replaced by taking adrift one magnet limb, with its coil, from the wheel.

Generally a double covering of the wires is sufficient and only in the case of high tension excitation or high peripheral speeds are wires of triple cotton covering or a double cover of spinning and one cover of braiding used.

55. **Exciting Current.**—The current for exciting the field magnets is conducted through brushes to two slip rings, which require to be of ample dimensions in order to carry the rated current without undue heating. It has been found an average good value to employ a current density of 100 amperes per sq. in. between the gunmetal slip rings and carbon brushes, and 400 amperes per sq. in. if the brushes are of copper.

56. **Material and Labor Costs.**—As already pointed out, the designer has to study the choice of the material, the constructional details, the workshop methods, the material and labor costs, in order that he may be able to judge if, with his best electrical and magnetic design, he can really obtain the cheapest machine.

Before entering into the discussion of alternator design, it will be found useful as preliminary guiding information, to give the standard material and labor costs of different parts of the generator. The designer keeping these figures in mind, will be able to weigh the results obtained and so note how they affect his different designs and costs. Figs. 14, 15 and 16, indicate the weights, material and labor costs of standard polyphase generators. In Fig. 15, the prices of materials are given in English shillings. (The value of an English shilling is about 24 cents U. S. A. money.)

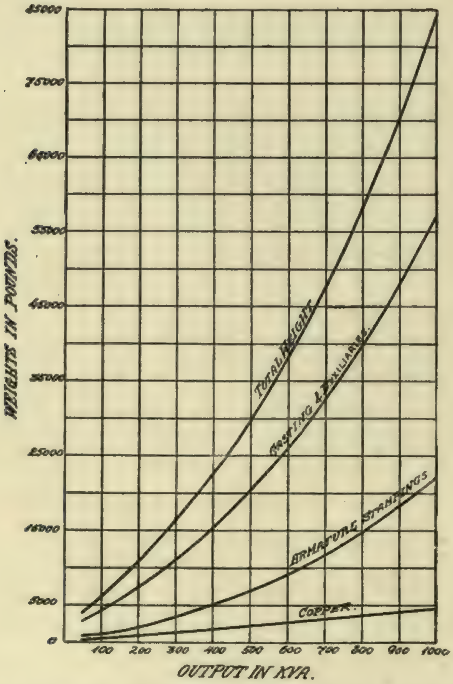


FIG 14.—AVERAGE MATERIAL WEIGHTS OF STANDARD MEDIUM SPEED, 50 CYCLE, POLYPHASE ALTERNATORS.

57. Example 1.—The designer is in possession of a specification, which requires him to design a 600 KVA. standard polyphase alternator, of the revolving field type, to deliver current at a periodicity of 50 cycles per second, when running at a speed of 250 r. p. m.

Solution.—The designer before entering into the design, will proceed as follows to obtain from the curves given in Figs. 14, 15 and 16, the weights, approximate prices of material and labor costs for such a machine.

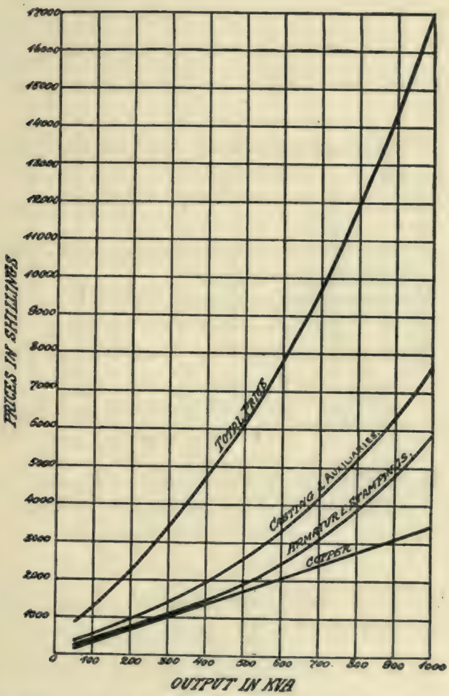


FIG 15.—AVERAGE MATERIAL PRICES OF STANDARD MEDIUM SPEED, 50 CYCLE, POLYPHASE ALTERNATORS.

From Fig. 14, it will be seen that the total weight of copper in the armature and field windings will amount to about **2,800** lbs.; the weight of the sheet iron in the armature core equals **9,200** lbs.; and the castings with auxiliaries equals **26,000** lbs. The total weight of the alternator without exciter will then amount to **38,000** lbs.

From Fig. 15, the cost of the copper will equal **2,000** shillings; the cost of the finished and annealed stampings for the armature coil will equal **2,400** shillings; and that of the castings and auxiliaries **3,300** shillings. The total material cost of the alternator will then equal **7,700** shillings. The rates given in Fig. 15 are based on modern workshop methods and the standard scale of wages customary and cost of materials in England. Similar curves can be readily plotted for costs in other countries.

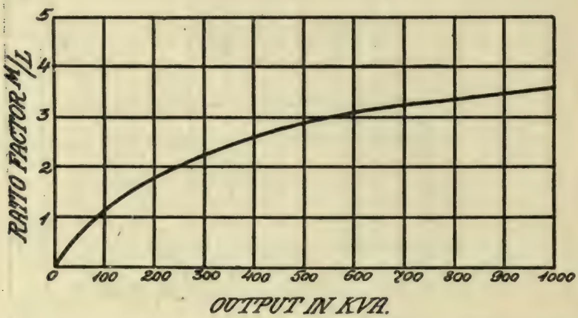


FIG. 16.—CURVE OF RATIO BETWEEN MATERIAL AND LABOR COSTS OF STANDARD MEDIUM SPEED, 50 CYCLE, POLYPHASE ALTERNATORS.

From the curve Fig. 16, the *ratio* between *material* and *labor* cost for the generator under consideration, is about 3 to 1, from which the shop labor costs of 2,550 shillings are obtained, where M and L equal material and labor, respectively.

It may be pointed out, that the greater the capacity of the alternator the greater will be the ratio $M \div L$.

CHARACTERISTIC DATA.

58. Characteristic Data.—The basis for the calculations of any machine is formed by the designer on the standard characteristic data supplied to him, from which he provides a generator to deliver a certain current at a certain terminal voltage and frequency.

The characteristic data of an alternator are as follows:

The normal capacity in *K.W.* and in *KVA*.

The normal working pressure on the line, in volts.

The normal speed in revolutions per minute.

The number of cycles per second or the alternations per minute.

The number and connection of phases.

Further, if not specified, the values of efficiencies must be decided upon and the permissible amount of inherent regulation is to be fixed.

59. Kilo Watts, Kilo Volt Amperes and Horse Power.—From the data of *K.W.* and *KVA.* the designer learns what capacity the prime mover must have and for what output the generator must be designed. Supposing that an alternator has to supply x *K.W.* to a power circuit of induction motors, and assuming the line load has a power factor of $\cos \varphi$, then the generator must be capable of developing $x \dfrac{K.W.}{\cos\ \varphi} = x\,KVA.$; that is, the generator is to be rated for the normal output in *KVA*.

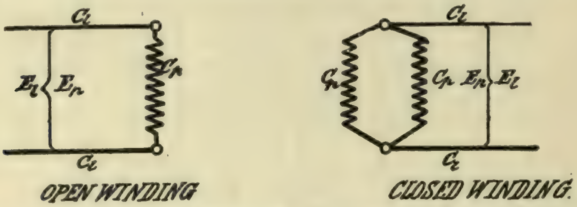
The size of the prime mover will be calculated on the basis, that it has to cope with the specified *K.W.* on the line and with the additional losses in the generator. Therefore, if the generator efficiency on inductive full load is equal to η, the capacity of the engine in horse power has to be equal to $\dfrac{K.W.}{\eta \times .746}$

60. Example. 2.—Determine the size of the prime mover and the rating of the generator, when as alternator it has to deliver 600 K.W. to a motor and lamp circuit with a power factor of .8.

Solution.—The rated capacity of the generator will be $\frac{600}{.8} = 750$ *KVA.*

If the efficiency on full inductive load is equal to 94%, then the capacity of the prime mover will be $\frac{600}{.94 \times .746} =$ **860** *HP. Ans.*

Supposing the generator has to supply a lighting circuit, that is, a circuit without inductance. The power factor is then



OPEN WINDING　　CLOSED WINDING.

FIGS. 17 AND 18.—ARMATURE CIRCUITS OF SINGLE-PHASE ALTERNATORS.

$\cos. \varphi = 1$ and the rated capacity of the alternator will be **600** *KVA. Ans.*

The horse power of the engine remains practically the same as before, because generally there is only a small difference between the efficiencies on inductive and non-inductive full loads.

61. Voltage and Current of Single Phase Machines.—The normal working pressure between the mains and the number and connections of the phases are the conditions next to be considered.

In the case of a *single phase* circuit, the line pressure E_l is the same as the voltage generated in the armature winding, E_p, provided that the alternator has an *open* winding, corresponding to Fig. 17, so that the armature current C_p is identical with that of the line current C_l.

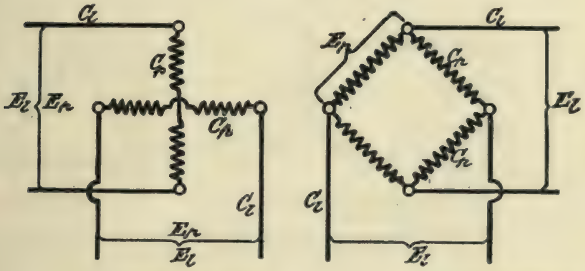
If the armature winding is *closed*, as in Fig. 18, each section will carry only one-half of the line current C_l and the conductors are to be dimensioned accordingly, that is, for a current equal to $\frac{C_l}{2}$.

The output of the above machine, with an open armature winding

$$= 1{,}000 \times KVA. = E_p\, C_p = E_l \times C_l \ldots\ldots\ldots (\mathbf{1})$$

and with a closed armature winding

$$= 1{,}000 \times KVA. = 2E_p\, C_p = E_l \times C_l \ldots\ldots\ldots (\mathbf{2})$$



OPEN WINDING CLOSED WINDING

FIGS. 19 AND 20.—ARMATURE CIRCUITS OF TWO-PHASE ALTERNATORS.

62. Two Phase Machines.—For a *two phase* generator with *two independent* phases as shown in Fig. 19, the line pressure E_l is equal to the voltage of each phase E_p and the same current C_p passes through each phase winding as through the main C_l. For instance, in a 600 *KVA.* two phase generator of 2,000 volts terminal pressure, the current will be 150 amperes *in each phase.*

If the alternator possesses an armature corresponding to Fig. 20, the voltage of each of the four armature sections or phases, E_p will equal $\frac{E_l}{1.41}$ and the current in each of the four phases C_p, will equal $\frac{C_1}{1.41}$ which in this case equals 107 amperes.

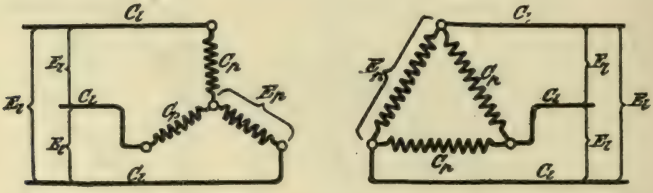
The output of the above machine with the *open* armature winding of *two independent* circuits

$$= 1{,}000 \times KVA. = 2E_p\, C_p = 2E_1\, C_1 \ldots\ldots\ldots (3)$$

and with the *closed* winding

$$= 1{,}000 \times KVA. = 4E_p\, C_p = 2E_1\, C_1 \ldots\ldots\ldots (4)$$

63. Three Phase Machines.—In *three phase* work two principal connections are in use, the *star* and the *delta* connections. In a three phase generator which produces a terminal pressure of E_1 volts, with a *star* connected armature, Fig. 21, the phase voltage E_p will equal $\frac{E_1}{1.73}$ volts and the current in each phase C_p as well as that in the line C_1 will be the same.



STAR CONNECTION DELTA CONNECTION.

Figs. 21 and 22.—Armature Circuits of Three-Phase Alternators.

Supposing that the generator armature is of the *delta* connection, Fig. 22, and the line pressure is E_1 volts, then each phase winding E_p of the armature has to be designed for the tension of E_1 volts and for a current C_p of $\frac{C_1}{1.73}$ amperes.

The output of a three phase machine with the *star* connected armature,

$$= 1{,}000 \times KVA. = 3E_p\,C_p = 1.73\,E_l\,C_l \ldots\ldots (\mathbf{5})$$

and with the *delta* connected armature

$$= 1{,}000 \times KVA. = 3E_p\,C_p = 1.73\,E_l\,C_l \ldots\ldots (\mathbf{6})$$

64. Example 3.—Find the phase voltage and the armature current of a 100 *KVA.* generator, when working as (1) a single phase, (2) as a two phase, or (3) as a three phase alternator, with a line voltage of 400 volts.

65. Solution.—Referring to Par. **61**, it is found, that for a single phase generator with an *open* armature winding, the phase voltage E_p is equal to the line voltage E_l, which in this case is 400 volts; and the armature current C_p is equal to the line current C_l, which in this case is 250 amperes.

Substituting these values in equation (**1**), we have

$$400 \times 250 = 400 \times 250 = 100{,}000\ VA = 100\ KVA.,$$

then the phase voltage $E_p = \mathbf{400}$ volts, and the armature current $C_p = \mathbf{250}$ amperes. *Ans.*

If a closed armature winding is used, from Equation (**2**) we have $2E_p\,C_p = E_l\,C_l = 1{,}000 \times KVA.$, where *each* section of the winding will carry a current equal to $\frac{C_l}{2}$;

therefore, $\frac{C_l}{2} = \frac{250}{2} = 125$ amperes; whence,

$$2 \times 400 \times 125 = 400 \times 250 = 100\ KVA.$$

In this case the phase voltage $E_p = \mathbf{400}$ volts and the current per section $C_p = \mathbf{125}$ amperes. *Ans.*

Two Phase Generator: In the case of a two phase generator with an *open* armature winding, we have from Equation (**3**),

$$2E_p\,C_p = 2E_l\,C_l = 1{,}000 \times KVA.,$$

which in the present case is equal to $2 \times 400 \times 125 =$

100 *KVA.*; and as the *same* current passes through *each* phase winding as through the mains, the phase voltage $E_p = \mathbf{400}$ volts and the current per phase $C_p = \mathbf{125}$ amperes. *Ans.*

If the two phase generator has a *closed* winding corresponding to Fig. 20, we apply Equation (**4**), in which case

$$E_p = \frac{E_l}{1.41} = \frac{400}{1.41} = 283 = E_p;$$

and

$$C_p = \frac{C_l}{1.41} = \frac{125}{1.41} = 88 = C_p; \qquad \text{whence,}$$

$$4 \times 283 \times 88 = 2 \times 400 \times 125 = 100\ KVA.$$

Therefore the phase voltage, $E_p = \mathbf{283}$ volts and the current per phase $C_p = \mathbf{88}$ amperes. *Ans.*

Three Phase Generators: In the case of a *star* connected three phase armature, where $\frac{E_l}{1.73} = E_p$ and $C_p = C_l$, we apply Equation (**5**).

Substituting the values given, we have:

$$3 \times 231 \times 144.5 = 1.73 \times 400 \times 144.5 = 100\ KVA.$$

Therefore, the phase voltage $E_p = \mathbf{231}$ volts and the three phase *armature* will carry a current of **144.5** amperes. *Ans.*

A delta connected three phase armature will generate under the same conditions, a current of $\frac{C_l}{1.73} = C_p$ with a voltage $E_p = E_l$, and applying Equation (**6**), we get,

$$3 \times 400 \times 83.5 = 1.73 \times 400 \times 144.5 = 100\ KVA.$$

Therefore the armature current will equal **83.5** amperes and the phase voltage **400** volts. *Ans.*

66. Winding Used In Modern Practice.—Going into details here, it may be mentioned, that practice leans in most cases toward the employment of alternators with *open windings*, which in the three phase system is the *star* connection.

67. Speed.—The normal speed of the generator is very often specified; if not, the choice is left to the designer. With a given frequency the speed is limited beforehand to certain values and the choice amongst them is influenced by the maker of the prime mover, whose engine cannot run below or above a certain speed.

In most cases the generator designer tries to push the speed upwards, as with higher speed the alternator becomes lighter and consequently cheaper. But at the same time one must not forget to take into account the efficiency and paralleling question.

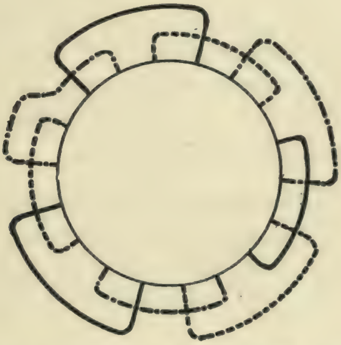


FIG 23.—WINDING DIAGRAM OF A THREE PHASE ALTERNATOR WITH AN ODD NUMBER OF POLE PAIRS.

In the case of a generator with a large number of poles, it is often found advantageous to make the number of pole pairs an *even* number, so as to avoid any dissymmetry in one of the armature phases and also to eliminate the employment of a hand wound coil.

Fig. 23 shows clearly the winding of a three phase armature with an *odd* number of pole pairs.

68. Speed Variation.—As a general rule the alternator designer expects a small variation in speed of the prime mover, when the load is varied from full load to zero, and consequently when designing the excitation, one has not to make a considerable provision to cover this drop in speed.

69. Frequency.—The frequency of the alternations of the current is the principal characteristic of the alternating current system. For instance, in connection with a certain prime mover of, say, 500 revolutions per minute, a 25 cycle generator will be of much smaller diameter, but of considerably larger width than a 50 cycle machine. The reason for this is: the 50 cycle alternator has double the number of poles of that of the 25 cycle machine, consequently the first machine must have a larger bore.

In the design of alternating current machines it is necessary to consider, step by step, how the different items are influenced by the frequency. For instance, the permissible iron densities will be higher for a low frequency generator, than for one of higher frequency, when considering a certain value of iron loss.

70. Law of Speed and Frequency.—For a fixed frequency the number of applicable speeds is limited, because the number of cycles is equal to the number of pole *pairs* p, multiplied by the number of revolutions per second N; that is:

$$p \times \frac{N}{60} = n \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(7)}$$

71. Example 4.—A generator running at the speed of 600 revolutions per minute N, having a field system of 10 poles, that is, 5 pole pairs p, will generate a current at 50 cycles. See Formula (**7**).

Example 5.—Take the case of a 12 pole machine in stock, which has to generate a current at 75 cycles. Under these circumstances, at what speed must the generator be driven?

Solution: Applying Formula (7) we have $p = \frac{12}{2} = 6$; $n = 75$. Therefore the speed is **750** r.p.m. *Ans.*

Example 6.—Supposing it is required to design an alternator to give a specified output at a frequency of 40, for direct coupling to a steam engine and the engine maker limits the applicable speeds to between 270 and 310 revolutions, what would be the most favorable speed?

Solution: For the generator in question, there are two suitable numbers of revolutions, namely 267 and 300. The first speed requires an 18 pole generator, the second speed corresponds to a machine of 16 poles. Under these conditions one would decide in favor of the higher speed, that is 300 r. p. m.

72. Standard Frequencies.—Practice has adopted the 40 to 60 cycle generators for lighting as well as for power work, but 25 cycle alternators are used with advantage where the load consists only of motor work.

Low Frequency: In the design of low frequency flywheel generators, one should bear in mind the difficulties which are presented, as with a comparatively small number of poles the diameter of the machine is of a very moderate size, and it becomes almost impossible to make an economical design under such circumstances, when the flywheel effect has to be placed in the magnet wheel.

High Frequency: On the other hand, a low speed high frequency alternator leads to an abnormally narrow and big machine, and in such cases the question of rigidity must be carefully considered. High frequencies of about 100 cycles are to be found in single phase systems, but there, too, it has become a rule to employ 40 to 60 cycle machines, and for such work, nearly all the makers have built their standard line of alternators.

Frequency and Speed: With the present large field of frequencies and with the great range of available speeds now obtainable, it is very common to find alternators of large capacity, which are designed as two pole machines, also generators with a large number of poles, as many as 80, for comparatively small outputs.

73. Electrical Characteristics.—The electrical characteristics of alternators, must be dealt with on the basis of experimental data, before entering into the discussion of their design.

These characteristics are: the *efficiency* and the *inherent regulation.*

74. Commercial Efficiency.—The commercial efficiency of a generator is defined as the *ratio* of its useful output to the input, where the output is equal to the electrical energy measured at the terminals of the alternator and the input is the sum of the useful output plus the *variable* and *constant* losses.

LOSSES.

75. Losses.—The variable and constant losses are as follows:

1. The friction losses (1) between the revolving part and the bearing, and (2) the rotating wheel and the air.

2. The hysteresis and eddy current losses in the armature and field iron.

3. The excitation losses in the field coils.

4. The energy consumption in the armature copper.

Losses **3** and **4** are usually termed the *Copper Losses,* and **2**, the *Iron Losses.*

76. Classification of Losses.—The classification of the above into constant and variable losses, will greatly facilitate the reading of the test data as well as the fixing of the different items of loss in the design. For instance, very often it is specified, that the efficiencies expressed in percentage of the input, shall be nearly constant throughout a big range of the external load. In this case it is obvious that the constant losses are to be kept low and the variable losses may be taken somewhat higher. The required condition is obtained, without any considerable sacrifice in the commercial design, by increasing the current density in the armature conductors slightly more than usual.

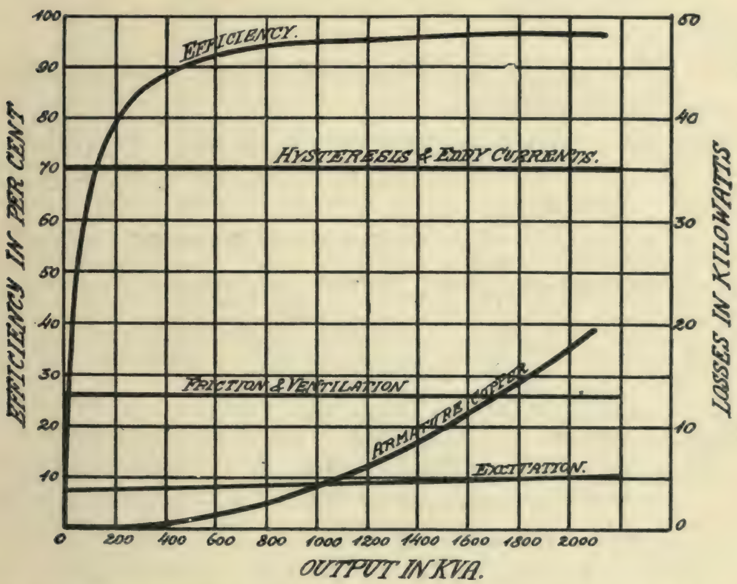


FIG. 24.—TEST CURVES SHOWING LOSSES AND EFFICIENCY OF A 1,600 KVA., 450 REVS , 45 CYCLE, THREE PHASE ALTERNATOR.

The test curves, Fig. 24, show distinctly, which losses belong to the respective classes.

77. Constant Losses.—The friction and iron losses are strictly constant, the energy required for the excitation is an item which contributes to the constant as well as to the variable losses. On the other hand, the armature copper loss is a strictly variable one and its curve in terms of the output of the generator is a *parabola;* that is, if the load on the alternator is doubled, the armature copper loss is quadrupled.

The no load excitation loss can be termed a constant loss, but the excess of the excitation energy is approximately proportional to the generator load.

The above rules hold good under condition of constant temperature.

78. Efficiency.—The commercial efficiency can be expressed by the formula,

$$Efficiency = \frac{W}{W + W_i + W_m + W_a + W_f} \quad ..(8)$$

in which

W = Output of the generator,
W_i = Iron losses,
W_m = Field copper losses,
W_a = Armature copper losses and
W_f = Friction losses.

79. Example 7.—Supposing in a three phase generator of 1600 *KVA.* normal rating, the following losses have been measured: Iron loss, 35 K.W.; excitation loss, 5 K.W.; armature loss 11.5 K.W.; friction and ventilation losses 13 K.W.

Solution: The efficiency of the generator at full normal load according to Formula (8) will be:

$$= \frac{1{,}600}{1{,}600 + 35 + 5 + 11.5 + 13} = \mathbf{0.96}.$$

That is, 96% of the *input* will be delivered as useful output. *Ans.*

80. Example 8.—The energy losses of the same generator when working at one half normal load, are indicated in the test curves, Fig. 24. What will be the efficiency at one half load, that is, at 800 *KVA?*

Solution: Referring to curves, Fig. 24, the iron losses are 35 K.W. as before; the excitation loss is 4 K.W.; the armature copper losses are 2.9 K.W.; the friction and ventilation losses remain the same as before, namely, 13 K.W. These make a half load efficiency of

$$\frac{800}{8\ 0 + 35 + 4 + 2.9 + 13} = \mathbf{0.935}\ ;$$

that is, 93.5% of the *input*, will be delivered as useful output. *Ans.*

81. Grouping of Losses.—The grouping of the different losses in their respective classes, expressed in *percentage* of the *input*, will be instructive and found useful, for the preliminary calculation of the efficiency on different loads.

On Full Load: On the fully loaded generator the input is $1{,}600 \div 0.96 = 1{,}666$ K. W., and the iron loss is 2.1% of same, because $\frac{35}{1{,}666} = 0.021$.

In the same manner, the friction and ventilation losses represent 0.78%; the excitation energy is 0.3% of the total input; and the armature current contributes 0.7% to the losses.

Consequently the fully loaded generator develops 2.88, say, 2.9% constant losses, 0.7 variable losses; and 0.3% of the *input* is utilized for the excitation.

On Half Load: On half load the input is $800 \div 0.935 = 855$ K. W. The constant losses give for the half load input, a percentage of $\frac{35 + 13}{855} = 5.65\%$, composed of 4.1% iron and 1.55% friction losses, which are double that of the corresponding figures for full load. The variable energy consumption in the armature copper, in percentage of the half load input, is somewhat less than one half of the corresponding percentage on normal output. The excitation energy adds 0.47% to the losses.

On Variable Loads: From the above calculations it is seen, that if the constant losses are $c\%$ at full load, they are very nearly $2c\%$ at half load and $\frac{4}{3}\,c\%$ at three quarter load, etc.; while if the variable loss is $v\%$ of the normal input, then at half load, about $\frac{v}{2}\,\%$ will be the result and at three quarter load about $\frac{3}{4}v\%$.

82. Example 8.—In order to illustrate the application of the above rules, take two points on the efficiency curve of the 1,600 *KVA.* generator Fig. 24, namely the full load efficiency which is 96.1% and the efficiency at half load 93.4%, and from these figures find the efficiency at three quarter load.

Solution: From Par. **81** we have the loss $3.9\% = c + v$; and the half load loss $6.6\% = 2c + \frac{1}{2}v$. From this we have: $2 \times 6.6 - 3.9 = 3c$, or $c = 3.1\%$; and $v = 3.9 - 3.1 = 0.8\%$.

In the expression of the three quarter load efficiency, Par. **81**, the constant loss percentage enters as $\frac{4}{3}c$; therefore $\frac{4}{3} \times 3.1 = 4.1\%$; the variable loss is $\frac{3}{4}v$, from which $\frac{3}{4} \times 0.8 = 0.6\%$ is obtained. Therefore the losses on three quarter load amount to 4.7% of the input; that is, the efficiency is equal to **95.3%**.

The efficiency curve of Fig. 24, indicates for three quarter load the same figure, namely **95.3%**. *Ans.*

From the above results it is seen, that if the efficiency for any *two* loads be known, the efficiency for *any other* load can be easily calculated with satisfactory exactness.

83. Example 9.—Supposing the full load efficiency of a generator is 92% and the half load efficiency is 86%, what will be the efficiency at two thirds load?

Solution: The loss in the first case is $8\% = c + v$; and in the second, $14\% = 2 \times c + \frac{1}{2}v$; from which we obtain $28 - 8 = 3c$, or $c = 6.66\%$ and $v = 1.34\%$ of the full load.

The losses at two thirds load will then be equal to $\frac{3}{2} \times 6.66 +$

$\frac{2}{3} \times 1.34 = 10.9\%$, which equals an efficiency of $100 - 10.9 = \mathbf{89.1\%}$ at two thirds load. *Ans.*

84. Subdivision of Losses.—By specifying any two efficiencies, the constant and variable losses are more or less fixed and the proper subdivision of the different items will be the next step. This work can be achieved on the basis of experimental data and empirical formulæ.

85. Friction and Ventilation Losses.—As the friction and ventilation losses are uncertain to calculate, it is found advisable to keep on the safe side when using the data given in the Table 8. Fig. 25 indicates the usual average friction and ventilation losses as experimentally found in commercial machines.

TABLE 8.—USUAL LIMITS OF FRICTION AND VENTILATION LOSSES, FOR DIFFERENT SIZES OF ALTERNATORS.

Output of Alternator.	Usual Limits in Per Cent.
10 KVA.	4.00 to 7.00
50 "	2.00 " 4.00
100 "	1.60 " 3.50
200 "	1.10 " 2.80
300 "	.90 " 2.30
400 "	.80 " 2.20
500 "	.75 " 2.10
750 "	.70 " 1.80
1,000 "	.50 " 1.25

The sources of the above losses are, the friction between the bearings and the shaft; friction between the brushes and slip rings; and the energy consumed due to the friction of the magnet wheel rotating in the air. The friction losses largely depend on the weight, speed and construction of the machine.

These losses can be kept well within the limits given in Table 8, by the skilful design of the bearings and shaft and an effective system of lubrication. The friction losses of the slip rings are usually comparatively small.

By adopting a magnet wheel of sound mechanical construction, the designer can considerably reduce the air friction losses, and also by remembering that the energy consumed by air friction can be effectively utilized for ventilating and cooling, in a properly arranged magnet wheel.

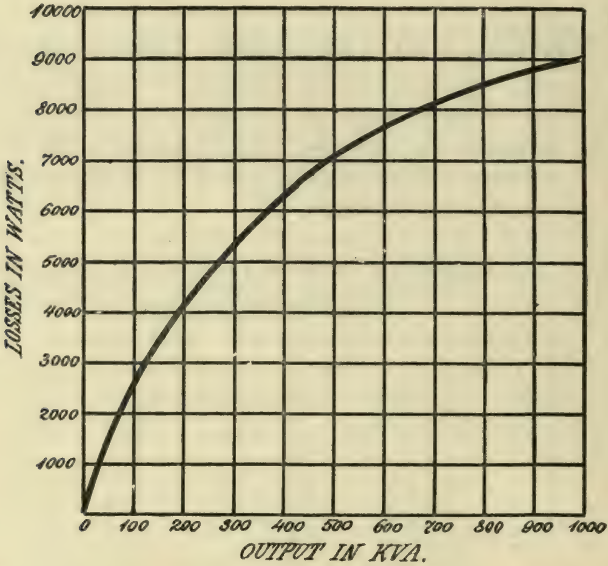


FIG. 25.—AVERAGE FRICTION AND VENTILATION LOSSES FOR DIFFERENT SIZES OF ALTERNATORS.

86. Bearing Friction Losses.—For the calculation of bearing friction losses, the formula

$$\text{Watts} = 0.9 \times d \times l \times \sqrt{v^3} \quad \ldots\ldots\ldots (\mathbf{9})$$

can be advantageously applied, where d = shaft diameter in inches; l = effective bearing length in inches; and v = peripheral speed in feet per second of the shaft inside the bearing. It is assumed that the specific pressure inside the bearing does not exceed the usual practical limit of about 600 lbs. per square inch.

When using formula (**9**), one must not forget that through inaccurate work in the shops or wear in the bearings, an eccentric displacement will likely occur between the armature and the magnet wheel, which involves a onesided magnetic pull. This additional pressure may amount to a value as high as 60% of the weight of the magnet wheel. It is, therefore, advisable for the designer to allow an ample margin when calculating the friction losses.

87. Iron Losses. The iron losses in an alternator are influenced by a large number of factors. The hysteresis loss is proportional to the *frequency,* is increased by increasing the *magnetic density,* and is influenced by the *wave form* of the armature current. When calculating eddy current losses a fourth factor has to be considered, namely, the *thickness* of the sheet iron used for the armature core.

Experience has proved, that in order to obtain the minimum eddy current losses a lamination of 0.02 to 0.01 inch is the most satisfactory for all requirements, because the employment of a finer gauge would only increase the cost of the stamped material and the labor in assembling, without the return of any appreciable advantages. Almost the *whole iron losses* are located in the armature iron as only a *small* loss takes place in the field system when excited by continuous current. The iron losses in the pole pieces are smaller, the smaller the opening of the armature slots.

It is advisable to use a lamination having a thickness of 0.04 inch for the pole shoes, regardless whether open slots or closed holes are stamped in the armature.

88. Magnetic Densities.—The values of magnetic densities in the armature core vary according to the frequency. Table **9** gives the limits of magnetic densities in magnetic lines per square inch section of the armature core as found in modern commercial designs.

TABLE 9.—USUAL LIMITS OF ARMATURE CORE DENSITIES FOR DIFFERENT FREQUENCIES.

Frequency.	Usual Limits in Lines Per Square Inch.
25	35,000 to 58,000
30	33,000 " 55,000
40	29,500 " 48,500
50	26,000 " 43.500
60	23,000 " 39,000
70	20,500 " 35,500
80	18,500 " 32,000
90	16,000 " 29,000
100	15,000 " 27.000
110	14,000 " 25,000
120	13,000 " 24,000

Fig. 26 gives the average values of densities in terms of the frequencies. This curve refers to the iron section *below* the teeth.

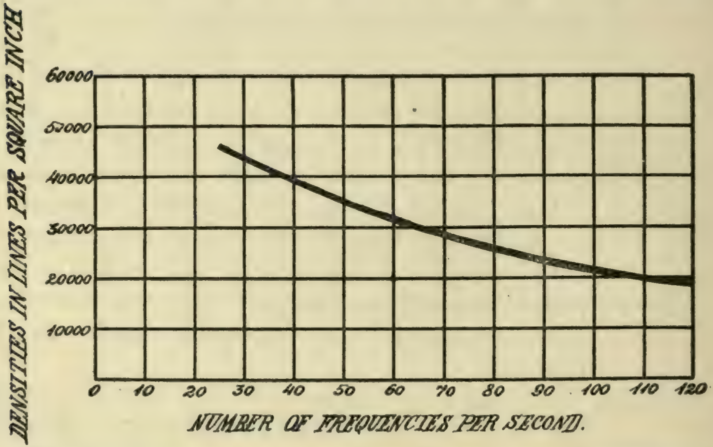


FIG. 26.—AVERAGE ARMATURE CORE DENSITIES FOR DIFFERENT FREQUENCIES.

the teeth. The permissible number of magnetic lines per unit section of the *teeth* is indicated in Fig. 27. On referring to Figs. 26 and 27 it will be noticed that the density in the teeth is *almost double* of that in the armature core.

89. Limits of Densities.—The difference in the limits of densities is due to the increasing or driving up of the induction in the teeth, which reduces the necessary section under the pole shoe and leads to an economical design and, besides, it stiffens or produces a more stable magnetic field next to the periphery.

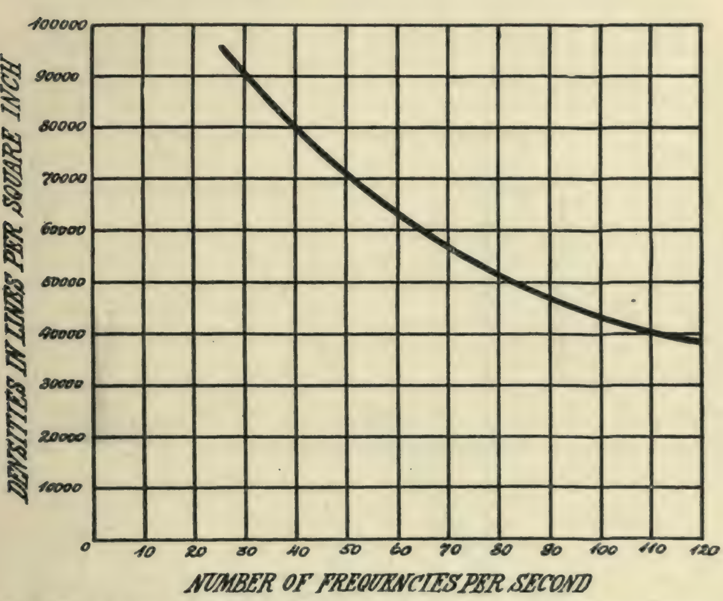


FIG. 27.—AVERAGE TEETH DENSITIES FOR DIFFERENT FREQUENCIES.

The same reasoning does not hold good for the armature core section, for it is necessary to choose and fix the magnetic densities in such a manner, that the resulting iron losses shall not exceed a certain limited amount, in order to obtain the best commercial efficiencies for different sizes of generators. As a good average figure, it may be noted that in standard designs the loss in the armature stampings is about 0.8 to 1.2 watts per lb. of effective iron material.

90. Choice of Magnetic Densities.—The choice of the magnetic densities for different frequencies is based on the loss of 0.8 to 1.2 watts per lb. when fixing the induction in the iron, the object being to keep the losses the same per *unit amount of material.*

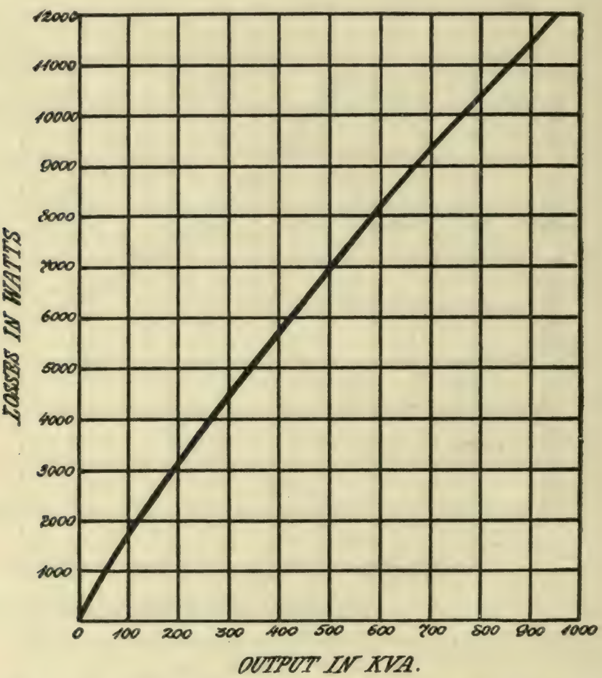


FIG. 28.—AVERAGE IRON LOSSES FOR DIFFERENT SIZES OF ALTERNATORS.

In Par. **91** some very useful data are collected, showing the total losses resulting from the hysteresis and eddy current losses in laminated armatures. It may be pointed out that if a lower efficiency is permitted the magnetic saturation may be driven higher than that stated in the curves, Figs. 26 and 27.

91. Iron Losses of Standard Generators.—The *total* iron losses of modern standard generators are given in terms of the machine capacity in Fig. 28, which, when compared with the curve in Fig. 14, will confirm the statement, that the armature iron loss is about 0.8 to 1.2 watts per lb. Table **10** gives the usual limit values of iron losses.

TABLE 10.—USUAL LIMITS OF IRON LOSSES FOR DIFFERENT SIZES OF ALTERNATORS.

Output of Alternator.	Usual Limits in Per Cent.
10 KVA.	2.30 to 4.40
50 "	1.90 " 3.50
100 "	1.60 " 3.00
200 "	1.20 " 2.50
300 "	1.15 " 2.15
400 "	1.10 " 2.00
500 "	1.00 " 1.90
750 "	.85 " 1.75
1,000 "	.65 " 1.45

The curves in Fig. 29 indicate the hysteresis and the eddy current losses in terms of the magnetic densities. The eddy current losses are given for two gauges of sheet iron. All the curves are based on a frequency of 100 cycles and the loss may be calculated for any other periodicity, by remembering that the hysteresis loss is *directly* proportional to the number of cycles and the eddy current loss proportional to the *square* of the frequency.

92. Example 10.—For one pound of laminated iron, the *hysteresis* loss at 100 cycles and an induction of 80,000, is equal to 10 watts. What is the loss under the same conditions at 40 periods?

Solution: According to Par. **91**, the loss will be

$$\frac{10 \times 40}{100} = 4 \text{ watts. } \textit{Ans.}$$

Example 10a.—For one pound of iron made up of 0.02 inch sheets, the *eddy current* losses observed are 4.5 watts, when the magnetic induction is 80,000 lines per square inch and the number of cycles is 100. What is the loss at 40 cycles?

Solution: The loss at 40 cycles, will be smaller in the ratio of $\frac{40^2}{100^2}$; that is, $4.5 \times \frac{40^2}{100^2} = \mathbf{0.7}$ watt. *Ans.*

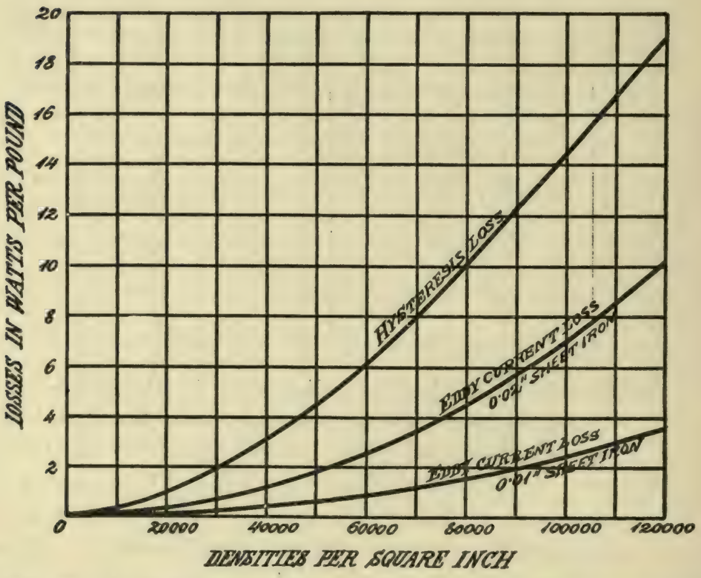


FIG. 29.—IRON LOSSES IN WATTS FOR DIFFERENT DENSITIES WITH A FREQUENCY OF 100 PER SECOND.

93. Effect of Machining.—It is important to keep in mind that the quality of the iron is much affected by the different operations such as machining, filing, etc., and the latter especially favors eddy currents inside the slots.

94. Armature Copper Losses.—The losses in the armature winding of a generator are on the average the smallest item of all the losses. Table **11** gives the limiting values of

TABLE 11.—USUAL LIMITS OF ARMATURE COPPER LOSSES FOR DIFFERENT SIZES OF ALTERNATORS.

Output of Alternator.	Usual Limits in Per Cent.
10 KVA.	4.00 to 6.00
50 "	1.85 " 3.60
100 "	1.50 " 3.00
200 "	1.20 " 2.30
300 "	1.15 " 1.95
400 "	1.10 " 1.75
500 "	1.00 " 1.50
750 "	.95 " 1.30
1,000 "	.85 " 1.15

the copper losses in terms of the generator capacity and Fig. 30 indicates the usual average armature losses.

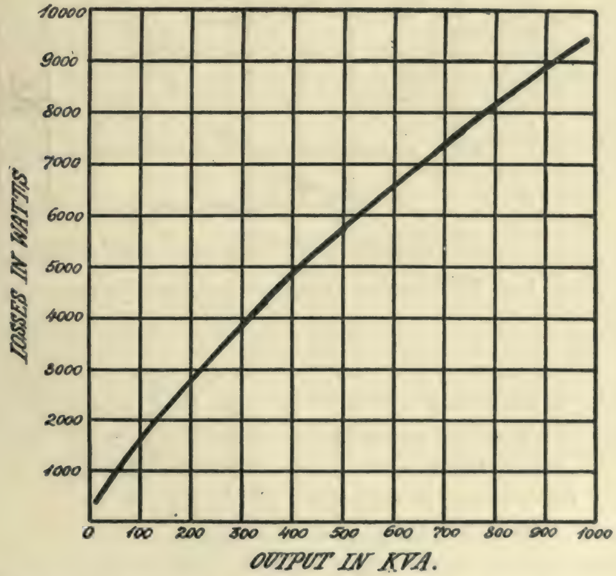


Fig. 30.—Average Armature Copper Loss for Different Sizes of Alternators.

The modern alternator with its improved ventilation and cooling arrangements, permits of a high current density of the copper, and the usual current densities allow an average copper loss of about 10 to 14 watts per lb. The economical use of the copper is a most important matter owing to its high cost.

95. Current Density.—In the design of stationary armature windings a current density (amperes per square inch of conductor section) of 2,000 amperes will create a temperature rise of about 40 degrees Centigrade. For large generators the armature current densities are somewhat lower than the above figure, and for small outputs higher.

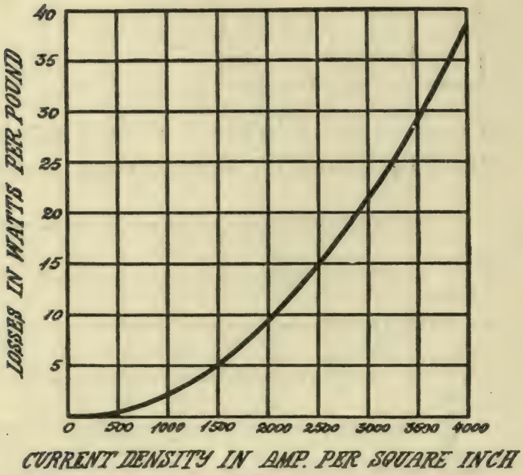


FIG. 31.—COPPER LOSSES PER POUND WEIGHT FOR DIFFERENT CURRENT DENSITIES.

In connection with this subject it will be useful to refer to Fig. 31, which gives the energy losses per unit weight in terms of the current density. The choice of the latter item is dependent on the permissible copper loss and temperature rise; consequently, if a higher efficiency is specified than the average commercial efficiency, or when the permissible temperature rise is lower than usual, then it is necessary to keep the armature current density *below* 2,000 amperes.

96. Loss in Windings.—The loss in the armature windings is equal to the *square* of the current multiplied by the armature resistance, that is:

$$W_a = C^2 R_2 \dots\dots\dots\dots (\mathbf{10})$$

where C is the armature current *per phase,* and R_2 the warm resistance of *all phases* in ohms.

97. Resistance in Windings.—The ohmic resistance of the armature winding is expressed thus:

$$R_2 = \frac{L_2 \times \omega}{q_2} \times m \times \frac{Z}{2} \dots\dots\dots (\mathbf{11})$$

where L_2 is the mean length of an armature turn in inches; q_2, the sectional area of the conductor in square inches; m, the number of phases; Z, the number of conductors per armature phase; and ω the specific resistance of the copper, which, for an average temperature may be taken as $\frac{0.8}{10^6}$.

98. Length of Mean Turn.—The sectional area of the copper, the value of the current, and the density are already fixed, which leaves only the mean length of a turn to be calculated.

An empirical formula may be used for the preliminary determination of the length of mean turn, but the proper way of obtaining the exact length, is to make a sketch from the actual dimensions of the armature. The empirical formula referred to above is only an approximate one and must be used with the necessary precautions. It is as follows:

$$\text{Length of mean turn} = L_2 = 2\ (l + k\ \tau) \dots (\mathbf{12})$$

L_2 = length of mean turn;

l = length of the armature core including the ventilating ducts;

τ = the pole pitch, that is, the peripheral arc from centre to centre of pole pieces; and

k = a *constant* depending on the type of winding and the value of the terminal pressure.

The *constant* for *polyphase* generators of *low* and *medium* pressure is 1.6 to 2; for *high tension* machines, 2 to 2.5; and for *single phase* generators it is about 20% less.

99. Definition of High Voltage.—It is difficult to give a distinct limit where to begin calling the pressure a high one, but it may be said that for generators of about 100 *KVA.* capacity, a tension of, say, 2,000 volts is considered enough to influence materially the economy of the design. Alternators of several hundred *KVA.* output may be considered high tension machines when the voltage exceeds 4,000 volts, and pressures above 6,000 volts are to be considered high for large generator sets.

100. Example 11.—The following example shows the method of calculating the mean length of the armature turns, the determination of the armature resistance and copper losses. A 300 KVA. three phase generator of 1900 volts terminal pressure has in its *star* connected armature 462 total turns. Each conductor consists of three parallel connected No. 9 S.W.G. wires, each wire having a diameter of 0.144 inch and a section of 0.0163 square inch. The bore of the generator is 51 inches; width of core, 10.5 inches; and the number of poles is 14. Find (1) the length of mean turn, (2) the armature resistance; and (3) the copper losses.

Solution: *Current density:* First, the copper section of the conductor is checked in order to see if it will carry the full normal current.

On referring to Par. **63**, we find that the current per phase will be $\frac{300,000}{1.73 \times 1,900} = 92$ amps. The conductor section is equal to $3 \times 0.0163 = 0.049$ square inch. Therefore the current density is $\frac{92}{0.049} = \mathbf{1880}$ amps. per square inch, (*Ans.*), which is a good figure.

Length of mean turn: The next step is to find the length of mean turn.

The bore being 51 inches, the circumference is equal to $51 \times 3.14 = 160.14$ inches and with 14 poles the pole pitch amounts to 11.14 inches. Further, the width of the armature core equals 10.5 inches.

From formula **12**, the mean length of a turn will therefore be equal to $2(10.5 + 2 \times 11.44) = \mathbf{66.8}$ inches, *Ans.*

It is of interest to state that in the machine in question, the length has been found by actual measurement to be **69** inches.

Copper loss: With the mean length of, say, 67 inches, the total length of the armature winding will be $462 \times 67 = 28,954$ inches, and, having a sectional area of 3×0.0163 square inches, the weight of the armature copper will amount to $28,954 \times 0.049 \times 0.319 = \mathbf{450}$ lbs. *Ans.*

From the curve in Fig. 31 it is found, that with a current density of 1,880, the energy loss in 450 lbs. of copper is equal to $450 \times 9 = \mathbf{4,050}$ watts. *Ans.* The same result would, of course, be obtained by calculating the armature resistance in ohms and multiplying the result by the square of the current in amperes, that is, C^2R.

Armature resistance: Supposing that the temperature of the air is 60 degrees Fahrenheit, the temperature rise in the armature 75 degrees, and the specific resistance of copper $\frac{0.8}{10^6}$ ohms per cubic inch. Then the resistance of the whole armature winding is equal to $\frac{28,954 \times 0\ 8}{0.049 \times 10^6} =$ **0.48** ohm. *Ans.*

At normal load the armature current is 92 amps.; therefore, the copper loss will amount to $92^2 \times 0.48 = \mathbf{4.060}$ watts which is practically the value 4,050 as found above.

TABLE 12.—DATA OF BARE AND DOUBLE COTTON COVERED WIRE, BRITISH S.W.G.

0	1	2	3	4	5	6
Number of British S.W.G.	Diam. inches. Bare Wire.	Area in Square Inches.	Lbs. per Ft. Bare Wire.	Ohms per Ft. at 60° Fahrenheit.	Max. Diam. of D.C.C. Wire.	Number of Wires per Inch D.C.C.
00	.348	.095115	.36636	.00008421	.363	2.7
0	.324	.082448	.31757	.00009715	.339	2.9
1	.300	.070686	.27227	.00011331	.315	3.2
2	.276	.059828	.23044	.00013387	.291	3.4
3	.252	.049876	.19211	.00016059	.267	3.7
4	.232	.042273	.16283	.00018947	.247	4.0
5	.212	.035299	.13596	.00022691	.227	4.4
6	.192	.028953	.11520	.00027664	.207	4.8
7	.176	.024329	.09371	.00032922	.191	5.2
8	.160	.020106	.077445	.00039836	.175	5.7
9	.144	.016286	.062730	.00049181	.159	6.3
10	.128	.012868	.049565	.00062243	.143	7.0
11	.116	.010568	.040707	.00075787	.131	7.6
12	.104	.008495	.032720	.00094286	.119	8.4
13	.092	.006648	.025605	.0012048	.107	9.3
14	.080	.005026	.019361	.0015934	.095	10.5
15	.072	.004071	.015683	.0019672	.082	12.2
16	.064	.003217	.012391	.0024897	.074	13.5
17	.056	.002463	.0094869	.0032519	.066	15.1
18	.048	.001809	.0069700	.0044262	.058	17.3
19	.040	.0012567	.0048403	.0063737	.050	20.0
20	.036	.0010179	.0039206	.0078689	.046	21.7
21	.032	.0008042	.0030978	.0099590	.042	23.8
22	.028	.0006157	.0023717	.0130070	.038	26.3
23	.024	.0004524	.0017425	.0177050	.034	29.4
24	.022	.0003801	.0014642	.021070	.032	31.3
25	.020	.0003142	.0012100	.025495	.030	33.3
26	.018	.0002545	.00098016	.031475	.028	35.7
27	.0164	.0002112	.00081365	.037916	.0264	38.3
28	.0148	.0001720	.00066263	.046558	.0250	40.0

101. Wire Gauges.—In the design and manufacture of electrical machinery in different countries, various standard sizes of wires are in use. In America, the American or

TABLE 12A.—DATA OF BARE AND SINGLE COTTON COVERED MAGNET WIRE, AMERICAN OR B. & S. GAUGE.

1	2	3	4	5	6	7	8
Size, B. & S. or Amer. Gauge.	Diam. Inches. Bare Wire.	Area, Cir. Mils. Bare Wire.	Diam. of S. C. C. Wire.	Number of Turns per Inch. S. C. C.	Lbs. per Foot, Bare Wire.	Lbs. per Foot, S. C. C. Wire.	Ohms per Foot, at 20° C.
1	.289	83,521	.309 [1]	3.23 [1]	.2533	.259 [1]	.000124
2	.258	66,564	.278 [1]	3.59 [1]	.2009	.206 [1]	.000156
3	.229	52,441	.249 [1]	4.01 [1]	.1593	.163 [1]	.000197
4	.204	41,616	.216	4.63	.1264	.1292	.000248
5	.182	33,124	.194	5.16	.1002	.1023	.000313
6	.162	26,244	.172	5.82	.0795	.0812	.000394
7	.1443	20,822	.154	6.5	.0630	.0645	.000497
8	.1285	16,512	.139	7.2	.0500	.0512	.000627
9	.1144	13,087	.124	8.1	.0396	.0406	.000791
10	.10190	10,384	.112	8.9	.0314	.0323	.000992
11	.09074	8,234	.101	9.9	.0249	.0257	.00126
12	.08081	6,530	.088	11.4	.0198	.0203	.00159
13	.07196	5,178	.079	12.7	.0157	.0161	.00200
14	.06408	4,106	.071	14.1	.0124	.0128	.00252
15	.05707	3,257	.064	15.6	.0099	.0103	.00318
16	.05082	2,583	.058	17.3	.0078	.0081	.00401
17	.04526	2,048	.050	20.0	.0062	.0064	.00506
18	.04030	1,624	.045	22.[illegible]	.0049	.0051	.00638
19	.03589	1,288	.041	24.4	.0039	.0041	.00804
20	.03196	1,021	.037	27.0	.0031	.00325	.01014
21	.02846	810	.033	30.3	.00245	.00260	.01275
22	.02535	643	.030	33.3	.00195	.00209	.01608
23	.02257	509	.028	35.7	.00154	.00164	.02030
24	.02010	404	.025	40.0	.00122	.00133	.02560
25	.01790	320	.023	43.5	.00097	.00106	.03225
26	.01594	254	.021	47.7	.00077	.00085	.04075
27	.01420	202	.019	52.6	.00061	.00068	.05135
28	.01264	160	.017	58.8	.000484	.00054	.0648
29	.01126	127	.015	66.7	.000384	.00043	.0818
30	.01003	101	.014	71.4	.000304	.00034	.1030

[1] Double cotton covered.

Brown & Sharp (B. & S.) gauge is adopted, and in Great Britain the Standard Wire Gauge (S. W. G.) is used. Tables 12 and 12A give these Wire Gauges.

102. Calculation of Resistance.—By the use of Table **12**, the calculation of resistances is simplified, as it is only necessary, after determining the length of the winding, to multiply the number obtained by that in column *4* in order to obtain the total resistance in ohms. For ''Data of Bare and Single Cotton Covered Magnet Wire,'' American or B. & S. Gauge, see Table 12A.

103. Excitation Losses.—In modern generator design where close regulation is necessary, it has been found advisable to make the ratio between the armature and field ampere turn about 1 to 3. This condition, combined with the permissible temperature rise, leads to a limit of the excitation losses in an alternator. Table **13** gives the usual limits of excitation losses for generators of various sizes.

TABLE 13.—USUAL LIMITS OF EXCITATION LOSSES FOR DIFFERENT SIZES OF ALTERNATORS.

Output of Alternator.	Usual Limits in Per Cent.
10 KVA.	1.80 to 4.75
50 "	1.35 " 4.00
100 "	1.00 " 3.50
200 "	.75 " 2.80
300 "	.65 " 2.50
400 "	.50 " 2.20
500 "	.50 " 2.00
750 "	.45 " 1.75
1,000 "	.45 " 1.25

The usual average values of excitation losses in terms of alternator capacity are indicated in Fig. 32.

104. Exciters.—The normal output of an exciter must be somewhat larger than the required energy for excitation, because it has to supply the losses appearing between the brushes and slip rings besides the energy necessary for excitation. It is advisable to provide an exciter which is capable of giving an output of about 25% above that required for excitation, on account of the watts lost in the field regulating resistance R_1 Fig. 1.

The necessary variation of the exciting current is generally obtained by regulating the resistance in the field circuit of the alternator, but the application of a regulating resistance in the shunt coils of the dynamo will be found not only economical but very convenient, as it permits a more close regulation than the alternator field regulator alone.

105. Exciting Current.—The watts required in the magnet coils are equal to the *square* of the excitation current multiplied by the warm resistance of the field winding, thus:

$$W_m = C_1^2 \times R_1 \quad \ldots\ldots\ldots\ldots\ldots (13)$$

where C_1 = the current in the coils, and
R_1 = the resistance of the coils.

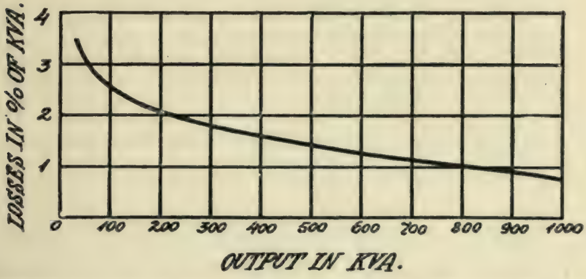


FIG. 32.—AVERAGE EXCITATION LOSSES FOR DIFFERENT SIZES OF ALTERNATORS

106. Resistance of Field Coils.—The ohmic resistance of the winding can be calculated by determining the total length of the coils in series, then multiplying the figure obtained by the specific resistance of the copper and dividing the result by the value of the sectional area.

The field coils, having a comparatively great winding depth, do not allow the same economical use of copper as the armature coils, because the cooling conditions for the inner layers are very unfavorable.

Assuming on the average a peripheral speed of 100 feet per *second,* the usual current density in the field copper for the maximum excitation current should not exceed 1,800 amperes per square inch, under the condition that the winding depth is less than 2 inches and that the permissible temperature rise is about 75 degrees Fahrenheit. Any departure from the above conditions, in one or the other way, allows an alteration in the value of the current density.

107. Length of Mean Turn.—Assuming that the pole core with its maget coil is already calculated and dimensioned, the determination of the mean length of a turn is preferably made from a drawing of actual measurements.

108. Advantages of Circular Poles.—It may be pointed out, that the mean length of a turn for a circular pole core section is the most advantageous, as with a given sectional area, the periphery of a circular core is smaller than for the oval or rectangular forms. The saving effected in the copper by using round pole cores is at times an appreciable amount. For instance, the periphery of a circular 8-square-inch section is 10 inches as against 12 inches circumference of a rectangular form with 2 × 4 inch sides.

It should be noted, however, that it is impracticable to make laminated pole pieces of circular section.

109. Advantages of Oval and Rectangular Poles.—If laminated poles are to be used, the rectangular shape is a necessity. In most cases of alternating current design it is difficult to comply with the requirements of circular pole sections, except for low speed machines, where the length of the armature core becomes approximately the same as the width of the pole piece.

In standard, medium or high speed generators the armature length is considerably larger than the width of the pole, and as a standard armature stamping is often utilized for various sizes of alternators the introduction of machines with the same bore but different core lengths usually takes place.

110. Example 12. A 300 KVA. three phase generator, running at a speed of 430 revs. per minute, has 14 poles, each carrying a coil of 130 turns of No. 4 S. W. G. wire. The coils are designed for the maximum number of 7,150 ampere turns with the full current of 55 amps. What is the loss in the field winding?

Solution: The sectional area of the wire being equal to 0.0423 square inch, the current density will be 1,300 amps. per square inch, which is a liberal figure considering that the peripheral speed is 96 feet per second, and the winding depth is about 1½ inches.

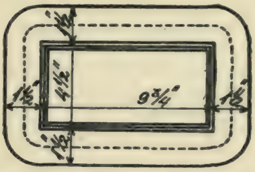


Fig. 33.—Length of Mean Turn in Field Coil.

Fig. 33 gives a sectional view of the pole with the magnet coil, from which we obtain the length of mean turn, viz., 34 inches; consequently the total length of the field winding will be 61,900 inches, corresponding to a weight of 840 lbs. (See Table **12**.)

From Fig. 31 we find an energy loss of 3,400 watts, when taking the temperature of the coils as 140 degrees F., the temperature on which the curve is based.

From Table **12** the cold ohmic resistance of the 14 magnet coils in series is equal to 1.0 ohm.

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THE DESIGN OF ALTERNATING GENERATORS AND SYNCHRONOUS MOTORS.

REGULATIONS:

111. Testing of Regulation.—The inherent regulation of alternators deserves the most careful consideration, as a small or reasonable voltage drop is the most satisfactory condition for central station work.

The direct method of determining the voltage drop, is to switch the normal full load on the alternator and measure the difference between the no-load and full-load voltage, when the excitation current and the speed are kept constant. When this test is executed under different excitations, that is, for different no-load voltages, one can see how the generator works under different degrees of magnetic saturation.

A properly designed alternator running at normal speed, with its rated normal excitation, should give a voltage drop which is only a small fraction of the open circuit pressure. Under these circumstances the generator will feed the line circuit satisfactorily without much attendance in the central station.

112. Workshop Tests.—To ascertain the regulation of a machine in the manufacturer's test room, the method given in the above Par. **111** is a very costly experiment, besides it is not always possible; therefore an indirect method has been devised, which is simple, reliable and cheap in its execution.

This method, which enables the designer to test the generator in the workshop, gives him a clear idea of the performance of the alternator under different working conditions, and discloses whether the various items have been properly valued.

To understand this important subject it is necessary to study the no-load or open circuit and the short circuit characteristics.

113. Open Circuit Characteristic.—The open circuit characteristic, Fig. 34, gives the E. M. F. of the generator in terms of the excitation current or of the equivalent field ampere turns, under the condition of a perfectly constant speed.

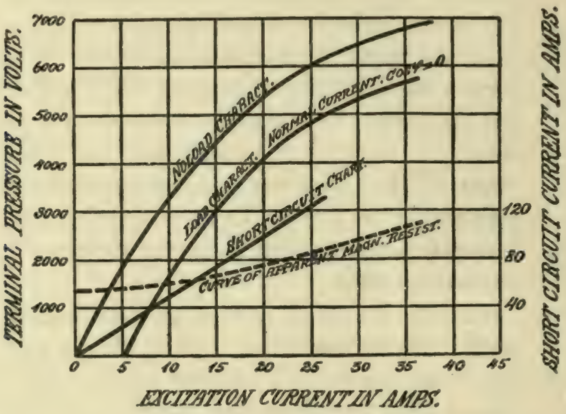

FIG. 34.—CHARACTERISTICS OF A 235 KVA., 50-CYCLE, STAR CONNECTED 3-PHASE ALTERNATOR.

The experimental determination of this curve is a very easy one, as it is only necessary to let the alternator run at its normal speed excited, and to measure the terminal pressure of the armature on open circuit, with various values of excitation.

This test gives the E. M. F. of the armature for the corresponding excitation, as the E. M. F. is directly proportional to the number of magnetic lines of flux which cut the armature coils. The no-load curve indicates the saturation of the magnetic circuit of the generator.

114. Saturation Point.—In alternator design, it is important to have a well saturated magnetic circuit within the working limits, and the normal pressure should be located over the knee or bend of the curve. If the normal working pressure is situated on the lower part of the curve which is under the knee or bend, the voltage drop will be large, producing an unsteadiness of the voltage, due to a comparatively small alteration of the excitation producing a considerable variation in the degree of saturation.

On the other hand, to work far above the knee or bend has also its disadvantages, namely, it involves a wide range of excitation regulation to effect a certain rise in the voltage of the armature, and such a wide range to work over is found inconvenient by the dynamo attendant when looking after the machinery.

From past practice it has been found best to aim at a normal saturation, where one per cent. voltage variation requires about 2.2 per cent. regulation in the exciting circuit.

115. Relation Between Field Ampere Turns and Armature Flux.—It must be clearly understood that the voltage on the armature terminals will always depend on the number of magnetic lines of flux which enter the plane of the armature winding. In an unloaded alternator there is no magnetomotive force in the armature which will oppose the effect of the field ampere turns and all the magnetic lines pass through the armature winding, except those which find their way through the leakage paths.

It has been found that the relation between the field ampere turns A_1 and the useful armature flux F_2, or its equivalent E. M. F., is as follows:

$$A_1 = R \times F_2 \ldots\ldots\ldots\ldots\ldots \textbf{(14)}$$

where R is the resultant of the various items of reluctance contained in the magnetic circuit of the machine. The above equation represents the *open circuit characteristic.*

The ratios between the corresponding ampere turns and flux are the variable values of R, and are known as the *apparent* magnetic resistances of the alternator. These values are indicated in Fig. 34, plotted in terms of the field ampere turns or excitation current. The curve may be plotted on a larger or more suitable scale if desired.

Later on, in Paragraph **131**, it will be seen that the absolute values of R are required for the predetermination of the no-load characteristic, and the form of the apparent reluctance curve is sufficient for the determination of the voltage drop from the test data.

116. Example 13.—Method of plotting the apparent reluctance curve from the test data.

Fig. 34 gives the open circuit characteristic of a 235 KVA. three-phase generator which has a normal terminal pressure of 5,200 volts with a star connected armature. By dividing the values of the excitation currents 30, 20 and 10 amps. by the corresponding values of the E. M. F., 6,500, 5,400, and 3,300 volts, we find the numbers whose relative values indicate the course of the apparent magnetic resistance in terms of the field excitation, and Fig. 34 shows that the same approaches a constant value for zero excitation.

The magnetic resistance R_s of the non-excited alternator plays an important role in the determination of the voltage drop.

117. Short Circuit Characteristic.—The short circuit characteristic Fig. 34, gives the current of the short-circuited armature in terms of the excitation ampere turns when the speed of the generator is kept constant. The experimental determination of the short circuit current is effected by exciting the field with a certain current and then measuring the current which flows in the armature circuit, when the terminals are connected together by means of copper bars having practically no resistance. For this test two measuring instruments are required, an ammeter in the field circuit and one in any one phase of the armature.

The above test can be made with ease and certainty, and with three or four readings, carefully taken, the short circuit characteristic can be drawn. Fig. 34 gives the short circuit test of a 235 KVA. three-phase generator, running at a speed of 429 r. p. m. and rated for a normal current at 26 amperes.

118. **Shape of Curve.**—As seen from the test data the short circuit characteristic is nearly a straight line, deviating from its course for very high excitations only.

It is necessary to keep in mind that the short circuit current lags 90 degrees behind the E. M. F. of the armature, because the ohmic resistance of the closed circuit is exceedingly *small* compared with the inductance.

119. **Effect of Armature Ampere Turns.**—The effect of the armature ampere turns being directly opposed to that of the field coils, the resultant magnetization will be just enough to produce the necessary small E. M. F. to overcome the ohmic resistance of the circuit and the attendant leakage field. Consequently it is obvious, that the short circuit current is a measure of the inductance and leakage effects of the armature which influence the inherent regulation.

120. **Ratio of Armature and Field Ampere Turns.**—If there were no leakage at all then the short-circuited ampere turns would be necessarily equal to that of the

field, and the ratio between them would be unity. The value of this ratio is always larger than 1, and for alternators with a large leakage coefficient it often reaches a value of 2.45. Such a value has been experimentally found for the 235 KVA. inductor type three-phase generator mentioned in Par. **117.**

For the standard inductor type alternator, this ratio factor is on the average equal to 2, and for revolving field machines about 1.2.

The extraordinarily high value in the case of the 235 KVA. generator, reveals its disadvantages in the design, which indicates that the ampere turns on the armature are too small and the iron body consequently too large, which results in an excessive leakage, requiring a strong field to keep the voltage drop within small limits.

From the above it will be seen that too much copper and iron has been used for a purpose which could be achieved much more cheaply by proper design.

121. Influence of Stray Field.—The influence of the stray field on the short circuit characteristic may be expressed as follows:

$$A_{1s} = A_2 \times k_s \quad \dots\dots\dots\dots\dots (\mathbf{15})$$

where A_{1s} is the amount of the field ampere turns;

A_2, the ampere turns of the short-circuited armature; and

k_s the ratio factor which characterizes the leakage conditions.

The method of calculating the ratio factor k_s and its effect on the voltage drop is shown in Par. **157**. The nearer the value of k_s is to unity, the better the alternator from the standpoint of regulation.

122. Load Characteristic.—In a loaded alternator, the current may be in phase with, or lagging behind the E.M.F., as the case may be. The armature ampere turns have a weakening effect on the magnetic field which cuts the armature coils and, consequently, there will be a drop in the terminal voltage.

If, for a certain armature current, the terminal voltages are measured for different excitations and the results plotted in terms of the field ampere turns, the so-called *load characteristic* of the alternator is obtained. Such a curve is given in Fig. 34, corresponding to the normal current on an inductive load with a power factor $\cos \varphi = 0$. The ordinate lengths between the open circuit characteristic and the load characteristic curves represent the drops in volts. For instance, the drop of the terminal voltage is 6,500 — 5,300 = 1,200 volts when the exciting current is 30 amperes, with an armature current of 26 amperes lagging 90 degrees behind the E. M. F.

123. Load Characteristics with Various Power Factors.

—Load characteristics indicating the inherent regulation can be obtained for different current values, as well as for different power factors, but in the first instance it is interesting to know the voltage drop on the armature when carrying the normal current with the power factors $\cos \varphi = 0$ and $\cos \varphi = 1$, the former being the inductive and the latter the non-inductive load.

It is important to note, that a small voltage drop on a non-inductive load, does not always result in good regulation on an inductive circuit, but if the inductive regulation is good, then the regulation on a non-inductive load will no doubt be satisfactory.

For an all round good regulation the inductive ($\cos \varphi = 0$) voltage drop gives the only reliable guide.

124. Necessity for Good Inductive Voltage Drop.

—It is best to design the alternator for a commercially good *inductive* voltage drop, especially if the generator is intended to supply a power circuit.

Fig. 5, gives the average values for fully loaded machines. For an intermediate load the drop can be approximately assumed from the ratio of the load currents; that is, if on full non-inductive load the regulation is 7% (curve B) then on half load it will be 3.5%.

Par. **130** explains the method of determining the drop exactly.

125. Determination of Voltage Drop.—The next step is to determine the voltage drop on an inductive load with the power factor $\cos \varphi = 0$, and an explanation of two experimental methods will greatly assist in understanding which elements affect the inherent regulation.

126. Prof. Arnold's Method.—The older method of Prof. Arnold deserves attention on account of its great simplicity, although the results obtained are far from being exact; however, it provides a basis for a reliable, corrected method.

The rule of the first method is expressed in the following equation,

$$A_1 = \overline{A_1} + A_{1s} \quad \text{..............} \quad \mathbf{(16)}$$

where A_1, is the value of the field ampere turns which corresponds to the open circuit voltage;

$\overline{A_1}$, the value of the field ampere turns which is required to generate an open circuit voltage equal to that at the terminals, when the armature carries a given current with a power factor $\cos \varphi = 0$;

and A_{1s}, the field ampere turns which will produce the specified current in the short circuited armature.

127. Application of Prof. Arnold's Method.—If the normal short circuit current, which lags 90 degrees behind the E.M.F., that is, has the power factor $\cos \varphi = 0$, counteracts A_{1s} field ampere turns, then the same armature current on an inductive load with a power factor $\cos \varphi = 0$ will also counteract A_{1s} field ampere turns. Therefore the application of this rule will take

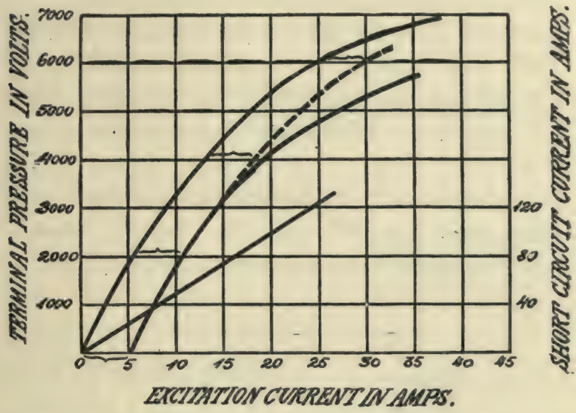

FIG. 35.—CHARACTERISTICS OF A 235 KVA., 50-CYCLE, STAR CONNECTED 3-PHASE ALTERNATOR.

the form indicated in Fig. 35, which gives the test results of a 235 KVA. three-phase generator.

The normal current of this alternator is 26 amperes with a terminal pressure of 5,200 volts, and the excitation required to obtain this current in the short circuited armature is equal to $A_{1s} = 5.06$ amperes.

128. On Inductive Load.—If, on an inductive load, the alternator with an excitation A_1 of 30 amperes produces an armature current of 26 amperes, then the terminal voltage of 6,000 volts will correspond to $30 - 5.06 = 24.94$ amperes exciting current in the open circuit characteristic, see Fig. 35.

The tension of the armature on open circuit, with 30 amperes field excitation, is 6,500 volts, so that the drop is equal to 6,500 — 6,000 = 500 volts. The actual voltage drop of the alternator in question has been found to be 1,200 volts, which is much more than the theoretically determined figure.

Take another value of field excitation, say 10 amperes, with an open circuit voltage of 3,300 volts. The test in this instance gave a voltage drop of 1,500 volts with 26 amperes inductive load on the armature, which is very close to the calculated figure, namely 1,800 volts, corresponding to 10 — 5.06 = 4.94 amperes excitation.

129. Consideration of Saturation.—In Fig. 36, as in other examples, it will be observed that the above method gives good results, when applied to that part of the open circuit characteristic which is under the knee or bend of the curve, but when applied to the curve above the bend, it produces values of the drop which are too small.

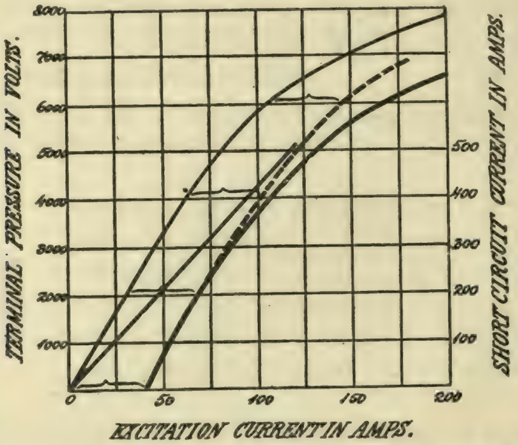

FIG. 36.—CHARACTERISTICS OF A 1,850 KVA., 50-CYCLE, STAR CONNECTED 3-PHASE ALTERNATOR.

The reason for this is, that the rule does not take into consideration, that the states of saturation are different, when the armature carries a short circuit current and when it delivers the same current to an external circuit at a high voltage. This is due to the fact, that the leakage conditions are generally more unfavorable in the case of a highly saturated magnetic circuit, than that of low saturation corresponding to the short circuited armature.

130. Second Method of Determining Voltage Drop.—The second method of determining the voltage drop from the open circuit and short circuit characteristics, takes into account the different degrees of magnetic saturation and leads to such rules which will enable the designer to calculate the machine characteristics with exactness, besides enabling him to fix the amount of regulation to be expected. The rule as it has been developed is embodied in the following equation:

$$A_1 = \overline{A}_1 + A_{1s}\left(\frac{\overline{R}}{R_s}\right)^2 \text{ ....} \textbf{(17)}$$

where A_1, $\overline{A_1}$ and A_{1s} have the same meaning as stated in Par. **126** and the factor $\left(\frac{\overline{R}}{R_s}\right)^2$ represents the ratio between the apparent resistances which correspond to the open circuit voltage of the load E. M. F. and to the non-excited state.

131. Determination of Inductive Regulation.—Equation (**17**) leads to a simple method of determining the inductive regulation of an alternator.

In this and Paragraph **132**, the test data of the 235 KVA. three-phase generator, Fig. 34, is used. Fig. 37 gives the no-load and the short circuit characteristics together with the curve R^2, which represents the square of the *apparent magnetic resistance* in terms of the excitation current.

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It is particularly pointed out, see Par. **115,** that the absolute values of R are not required, as the shape of the curve is sufficient.

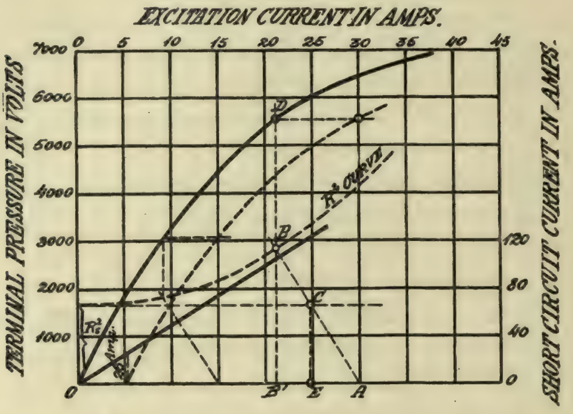


FIG. 37.—DETERMINATION OF THE INDUCTIVE COS $\varphi = 0$ REGULATION OF ALTERNATORS FROM THE NO-LOAD AND SHORT CIRCUIT CHARACTERISTICS.

132. Calculation of Inductive Regulation.—To determine the inductive regulation, proceed as follows: From the short circuit characteristic, take the field ampere turns corresponding to the current value for which the drop is to be obtained and deduct this number from the field ampere turns, corresponding to the particular field excitation for which the regulation is to be found.

In the present case the excitation is given in amperes and not in ampere turns; therefore, take the exciting amperes corresponding to an armature current of 26 amperes on the short circuit characteristic, namely, about 5.06 amperes, and deduct this from the field current (OA) of, say, 30 amperes, so obtaining the point E on the abscissæ line, Fig. 37. Erect at this point E a perpendicular and mark on it the point C, on the horizontal through R_s^2. Draw the line $A\ C$ until it cuts the curve representing the square of the apparent resistance, at the point *B*. Draw through *B* a perpendicular until it intersects the no-load saturation curve at *D*, and the voltage thus indicated is the pressure of the generator loaded with 26 amperes phase current with a power factor of zero (cos $\varphi = 0$).

This operation carried out for different field currents, gives the full load characteristic for a power factor cos $\varphi = 0$.

133. Rule for Calculating the Non-Inductive Regulation.

133. Rule for Calculating the Non-Inductive Regulation.—The inherent regulation of the generator on non-inductive load for any current at any power factor, can be easily determined by remembering the following rule:

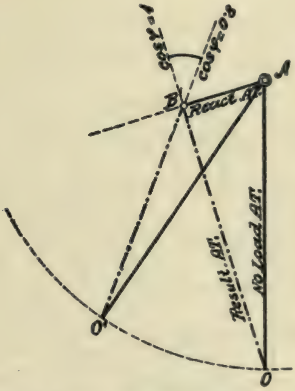


FIG. 38.—GRAPHICAL DETERMINATION OF LOAD M.M F. WITH GIVEN NO-LOAD AND REACTANCE M M.F.'S FOR DIFFERENT POWER FACTORS.

The reactive ampere turns of the armature, *A* B^1 in Fig. 37, corresponding to the field excitation *O A* and obtained by the method described in Par. **132,** are the sides of a triangle in such a form, that the reactive ampere turns as one side encloses with the third side an angle, which corresponds to the value of the power factor.

That is to say: For a power factor cos $\varphi = 0$ the angle is equal to $90 + 90 = 180$ degrees; for cos $\varphi = 1$ it is $90 + 0 = 90$ degrees, etc.

The above rule is also illustrated in the simple diagram Fig. 38. The triangle consists of the field turns $O\ A$ and the reactive turns $A\ B^1$ as two sides; $90 + \varphi$ as one of the angles; and the third side is represented by the field ampere turns, which correspond to the load voltage on the saturation curve. In this manner $O\ B^1$, Fig. 38, represents the resultant ampere turns with cos $\varphi = 1$, and $O^1\ B^1$ the resultant ampere turns with cos $\varphi = .8$.

134. Determination of Non-Inductive Regulation.—Fig. 39 shows the determination of the non-inductive regulation of the 235 KVA. three-phase generator, the characteristics of which are shown in Fig. 34.

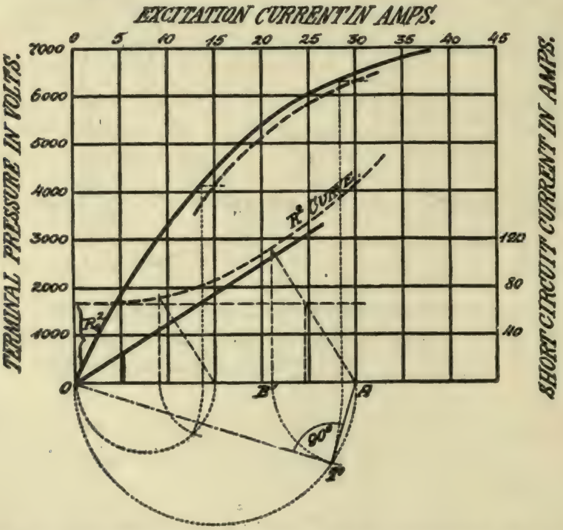


Fig. 39.—Determination of the Non-Inductive Cos $\varphi = 1$ Regulation of Alternators from the No-Load and Short Circuit Characteristics.

In order to obtain the terminal pressure on the armature carrying a current of 26 amperes at $\cos \varphi = 1$, the following operation has to be performed.

Supposing that the field excitation is 30 amperes, the reactive ampere turns $A B^1$ are first determined as in Par. **732**; then a semicircle with $O A$ as diameter is described on $O A$. This semicircle when intersected by $A B^1$ from center A, gives $O T$ as the excitation corresponding to the load voltage. It is obvious from the figure that $O T$ and $A T$ form an angle of 90 degrees, corresponding to $\cos \varphi = 1$. In the above case $O T$ is equal to 28 amperes and the load pressure, 6,300 volts.

135. Actual Load Characteristic.—The actual load characteristic of the 235 KVA. alternator, Fig. 34, indicates that with the above described method, the inherent regulation from the no-load and short circuit characteristics can be satisfactorily determined.

The design of an alternator with a specified regulation is therefore reduced to the proper predetermination of the open circuit and short circuit characteristics.

136. Elements which Affect Regulation.—The principal elements which affect the regulation of an alternator are as follows:

1. Voltage drop due to the ohmic resistance of the armature.
2. Voltage drop due to hysteresis and eddy currents.
3. Leakage of exciting field.
4. Leakage of armature field.
5. The demagnetizing effect of the armature ampere turns.

In a properly designed alternator, the two items 1 and 2 are so small that they may be neglected; but the magnetic properties mentioned under 3, 4 and 5 have to be carefully considered.

The action of the magnetic properties mentioned above will be best understood if the machine is looked upon simply as a circuit of magnetic lines.

137. Magnetic Circuits.—In a generator there are as many closed magnetic circuits as there are number of poles. For instance, Fig. 40 indicates the six closed circuits of a 6-pole revolving field type alternator, and as all these circuits are alike, it is sufficient to deal with only one of them.

Such a magnetic circuit consists of the *useful* and *leakage* paths, the former being represented by the lines through the wheel rim, pole core, pole shoes, air gap, slotted part of the armature and armature core, which return to the starting points by passing through the different parts in the reverse order.

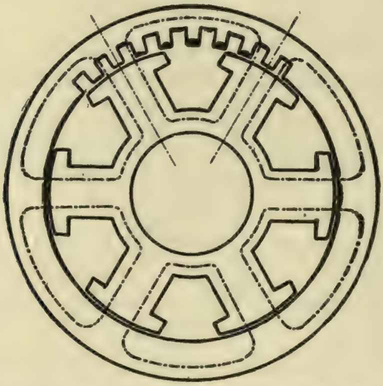


FIG. 40.—MAGNETIC CIRCUIT OF A 6-POLE GENERATOR.

The leakage paths are located in the space which surrounds the machine body, due to magnetic lines attempting to escape through the air, by passing from one part of the useful magnetic circuit to another of lower magnetic density.

The magnetic circuits which offer a certain resistance to the flow of the lines of magnetomotive force, have in their field ampere turns the source of the exciting magnetomotive force. The lines of useful magnetomotive force cut, so to speak, the armature winding and generate an E. M. F., which produces a current when the armature winding is closed.

The current carrying armature coils represent the source of another magnetomotive force in the magnetic circuit of the machine.

138. Treatment of Magnetic Circuit.—The treatment of the magnetic circuit in a manner similar to that of an electric circuit, is the simplest method to explain the somewhat complicated origin of the inherent regulation. Fig. 41, indicates the magnetic circuit of one pole of the machine illustrated in Fig. 40.

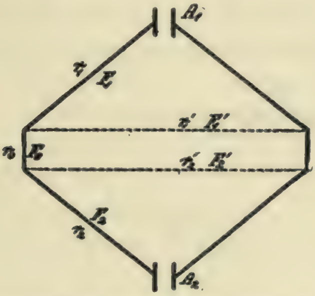


Fig. 41.—Hypothetical Representation of the Magnetic Circuits of a Generator.

The symbols used in Fig. 41, are as follows:

A_1, the ampere turns or magnetomotive force of the exciting field;

A_2, ampere turns or magnetomotive force of the armature winding;

r_1, reluctance of the field system consisting of the paths in the wheel rim, pole cores and pole shoes:

F_1, flux in the field system, that is, the number of lines of magnetomotive force passing through the field system;

r_1^1, magnetic resistance of the field leakage path;

F_1^1, flux or number of lines carried by the field leakage path;

r_0, magnetic resistance of the air gap;

F_0, flux in the air gap;

r_2, magnetic resistance of the armature system consisting of the teeth and of the core above the toothed part;

F_2, flux flowing through the armature system;

r_2^1, magnetic resistance of the armature leakage path; and

F_2^1, flux in the armature leakage path.

139. Magnetomotive Force.—The magnetomotive force, which may be expressed in ampere turns, is analogous to the E. M. F. of an electric circuit; the flux given in 10^6 lines is identical to the electric current, and the reluctance is the same for the magnetic circuit as resistance is for the electric circuit.

The symbolical expression of the reluctance is

$$r = \frac{l}{q \times \mu} \times 0.313 \ldots\ldots\ldots\ldots \mathbf{(18)}$$

where l = the length of a magnetic path of a section equal to q square inches, and μ = the permeability of the resistance material.

The latter symbol μ in the above magnetic formula (**18**), is analogous to the specific conductivity of an electric conductor.

It is obvious from Fig. 41, that the leakage lines passing through the dotted paths are entirely lost, from a useful point of view, and in consequence of this, the designer must make the resistance of the leakage path high and that of the useful circuit comparatively low.

This qualitative conclusion indicates, that in an electrically favorable design, the length of the useful magnetic circuits should be as small as possible, the sectional area ample, and that the saturation in the unit section should correspond to the highest permeability.

Further, it is necessary that the spaces between the useful paths of different magnetic density should be large, but at the same time should offer as small a sectional area as possible to the leakage lines, and that the pole pieces should be placed far apart from each other.

All these conditions cannot, however, be complied with, as it would involve a sacrifice of practically everything for the sake of good regulation, so making a very costly alternator.

The compromises which are to be effected in order to obtain an all round satisfactory machine, will be discussed later in the examples of design.

140. Reluctance.—The symbolical expressions of the reluctances of the different magnetic paths depending on the dimensions and forms of the iron and copper parts, are given in Pars. **141** to **153.**

These items are of the greatest importance, because the proper determination of the machine characteristics depends on the correct calculation of the different magnetic resistances.

With the careful determination of the no-load and short circuit characteristics, not only is the required regulation obtained within a specified limit, but expensive experiments and tests are unnecessary.

141. Calculation of Reluctance.—The magnetic resistances or reluctances of the various magnetic paths may be calculated on the basis of Equation (**18**), by referring to Fig. 42, which indicates by symbols the dimensions of the various parts.

It should be noted that the expressions of the reluctances, are obtained from hypothetical assumptions, simplified for practical use, so that they form more or less empirical formulæ of sufficient exactness for design purposes.

The revolving, alternate pole type generator will be discussed, because it is the most modern type of machine; but

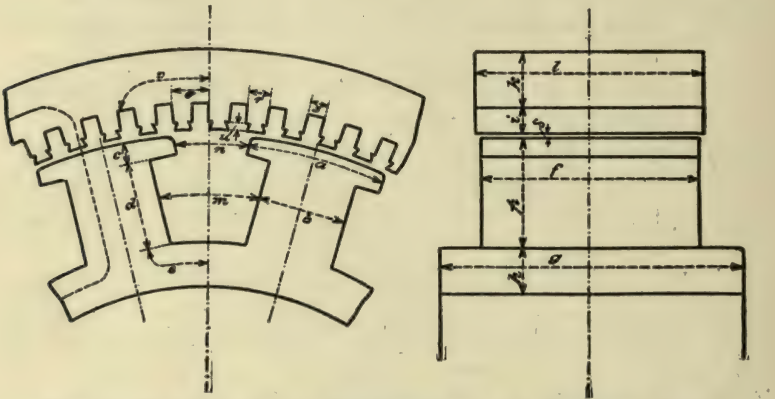


FIG. 42.—SYMBOLS OF THE DIMENSIONS OF THE MAGNETIC PATH.

it should be noted that the expressions may also be applied to the revolving armature type alternator.

In the following calculations the magnetic resistance of only one pole is dealt with.

142. Magnetic Reluctance of the Field System.

142. Magnetic Reluctance of the Field System.—The magnetomotive force of one magnet coil forces a certain number of lines through the rim of the wheel, the pole core and the pole shoes. The reluctance of the pole shoes is in most cases too small to take into account, so we write for the reluctance of the pole system:

$$r_1 = 0.313 \times \left[\frac{d}{b \times f \times \mu_p} + \frac{e}{2g \times h \times \mu_r}\right] \ldots \textbf{(19)}$$

For the definition of the various symbols see Fig. 42.

Further μ_r = the permeability of the iron in the wheel rim, and

μ_p = the permeability of the iron in the pole core; both these values vary with the *degree* of *saturation.*

143. Example 14.—Assume that the pole system of an alternator has the following dimensions:
$d = 10$ inches; $b = 6$ inches; $f = 17$ inches;
$e = 9$ inches; $g = 24$ inches; $h = 5$ inches. Substituting these values in Formula (**19**) and taking $\mu_p = 350$ for the pole core and $\mu_r = 150$ for the wheel rim, we obtain a *field system* reluctance value of

$$r_1 = 0.313 \left[\frac{10}{6 \times 17 \times 350} + \frac{9}{2 \times 24 \times 5 \times 150} \right] = \frac{1.65}{10^4}. \quad \textit{Ans.}$$

144. Reluctance of Air Gap.—The air path between the rotating and stationary parts, termed the *clearance*, contributes the greatest item to the apparent magnetic reluctance of the alternator and its calculation requires special attention, because the correct dimensioning of the air gap influences not only the electrical characteristics, but also the price of the machine.

The following expression has been found to give good practical results. The symbols referring to the demensions indicated in Fig. 42:

$$r_0 = \frac{1}{\dfrac{a \times r \times l}{o \times \delta} + \dfrac{l \times a \left(+ u \frac{s}{2} \right)}{o\,(u + \delta)}} \times 0.313 \ldots (\mathbf{20})$$

The above formula refers to armatures with open slots.

For closed, or slightly open, holes the whole pole shoe surface which is opposite to the toothed body has to be taken into consideration, so making the expression in this case:

$$r_0 = \frac{\delta}{l \times a} 0.313 \ldots\ldots\ldots\ldots\ldots (\mathbf{21})$$

It may be pointed out, that as a general rule the width of the pole is 1 to 1½ inches less than that of the armature, in order to effect the cutting of the armature core and winding by part of the stray lines of the field.

145. Example 15.—The large alternator mentioned in Par. **143** has a pole arc a of 8 inches; a slot width s of 1 inch; a total armature length l of 20 inches; a tooth pitch o of 2.4 inches; an air gap δ of 0.35 inch; a depth taken up by the fixing wedge and insulation material u of 0.3 inch; and a width of tooth r of 1.4 inches.

With this data and application of Equation (**20**), there is obtained an *air gap* reluctance value

$$r_0 = \frac{0.313}{\dfrac{8 \times 1.4 \times 20}{2.4 \times 0.3} + \dfrac{20 \times 8 \times 0.8}{2.4 \times 0.65}} = \frac{8}{10^4}. \quad \textit{Ans.}$$

This value is about 5 times larger than the reluctance of the field system for the saturation assumed in Par. **143.**

It will be found in course of the calculations of practical examples, that the results will be very close to the proportion of reluctances given herein.

146. Reluctance of Armature System.—The magnetic reluctance of the teeth and armature core is in most cases a small value, when compared with that of the field system and air path.

The following equation expresses the reluctance of the armature system:

$$r_2 = \left(\frac{i \times o}{a \times r \times l \times \mu_t \times j} + \frac{v}{2k \times l \times \mu_a \times j}\right) 0.313 \ldots (\mathbf{22})$$

For the definition of the various symbols, reference is made to Fig. 42.

Further μ_t = the permeability of the iron in the teeth;

μ_a = the permeability of the iron in the armature core, and

j is a constant depending on the amount of insulation in the armature core and in this case may be taken as 0.85 to 0.9.

147. Example 16.—In the foregoing calculations Par. **145,** the dimensions a, o r, and l are already given. The depth of the teeth $i = 2.2$ inches; $v = 10$ inches; and $k = 8$ inches; $r = 1.4$ inches.

The magnetic saturation corresponding to those of the field system are, $\mu_a = 640$ and $\mu_t = 230$.

From this data is obtained an *armature system* reluctance value as follows, by substituting the values in Formula (**22**):

$$r_a = \left(\frac{2.2\times 2.4}{8\times 1.4\times 20\times 230\times .9} + \frac{10}{2\times 8\times 20\times 640\times .9}\right)$$

$$0.313 = 0.54\times 10^{-4}. \quad \textit{Ans.}$$

which is about 30% of the reluctance value of the field system, or 6% of that of the air gap.

148. Reluctance of the Field Leakage Path.—In Fig. 43, seven distinct directions are indicated in which the magnetic lines may leak outside of the useful circuit. The magnetic lines passing in the direction of *6* and *7* are not actually lost to the useful armature magnetic circuit, providing that the precaution is taken of making the length of the armature core somewhat longer than that of the pole face. In this case the items *6* and *7* need not be calculated.

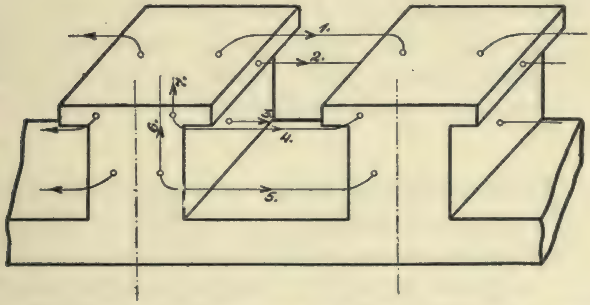


FIG. 43.—LEAKAGE PATHS OF THE FIELD MAGNET SYSTEM OF A GENERATOR.

In most cases the lines lost in the direction *4*, are too small to be considered and the same may be said about those of the path *1*, especially if the air gap has moderate values. For the sake of simplicity one neglects these items and it will be found that the following expression of the field leakage reluctance is entirely satisfactory, reference being again made to Fig. 42 for the meaning of the symbols:

$$r_1^1 = \frac{0.313}{\frac{4c \times f}{n} + \frac{4d \times f}{m} + \frac{4b \times d}{m + b}} \cdots\cdots (\mathbf{23})$$

149. Example 17.—The values *d, f* and *b* are already given in Par. **143;** and further $c = 1.4$ inches; $n = 6$ inches; and $m = 7$ inches. Substituting these values in Formula (**23**), we obtain as the reluctance value of the *field leakage path*:

$$r_1^1 = \frac{0.313}{\frac{4 \times 1.4 \times 17}{6} + \frac{4 \times 10 \times 17}{7} + \frac{4 \times 6 \times 10}{13}} = \frac{24}{10^4}. \quad \textit{Ans.}$$

This value is about 3 times larger than the reluctance of the air gap. The reason for this comparison will be found in Pars. **154** to **158**, where the leakage coefficient of the whole magnetic circuit is discussed.

150. Reluctance of Armature Leakage Path.—The calculation of this item is one of the most difficult tasks of the designer, as the conditions are far too complicated to take into account all the different factors, such as the class of winding, form of the coils, form of the armature magnetic field, saturation of the teeth, influence of the idle iron parts near to the armature body, etc.

It is considered satisfactory to calculate the value of the reluctance of the armature stray field within 10%.

Formula (**24**) will answer the purpose in most cases, especially if the reluctance items are considerable.

151. Directions of Lines of Armature Leakage Path.—Figs. 44 and 45 indicate the principal directions of the leakage lines. The number of lines lost in the paths *1* and *4* are generally negligible and only the leakage inside the slots, direction *2*, and that around the teeth faces, direction *3*, will be considered.

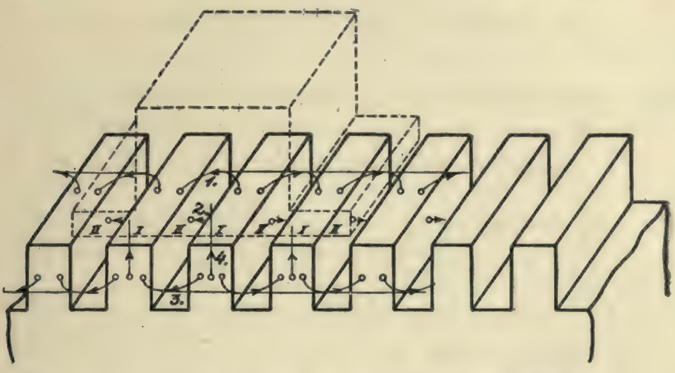


Fig. 44.—Leakage Paths of the Armature System of a Generator.

An additional loss of magnetic lines will be found around the inactive wires of the armature winding which project out of the iron core. Such leakage is considerable in a generator with a large number of poles, such as a machine of large diameter with a short armature. This item will

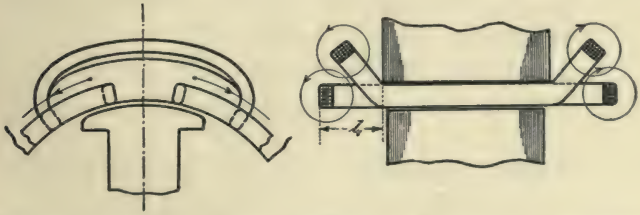


Fig. 45.—Leakage Paths around the Inactive Armature Winding.

be more important the higher the voltage of the machine, because in high tension windings the inactive wire must be increased to guard against breakdowns.

Fig. 45, indicates an assumption of the direction of the stray lines around the inactive wire of an armature winding.

152. Calculation of Armature Leakage Path Reluctance.—The expression of the armature leakage path reluctance, referring again to Fig. 42, is as follows:

$$r_2^{1}=\frac{0.313}{\frac{4i\times l\times o}{s(n+a)}+\frac{4i\times r[(a+n)+o]}{(a+n)\times o}+(a+n)+2l_1} \quad .(\mathbf{24})$$

The leakage lines of the inactive wires are assumed for an example, such as an armature with long coils as shown in Fig. 45.

153. Example 18.—In order to obtain the reluctance of the armature leakage path, the data required for the machine in question, Pars. **143** to **149**, is known with the exception of l_1, Fig. 45, which is equal to the length of the coil projection.

In the present case, the armature has coils of different lengths, consequently, a mean value has to be found which in this case is $l_1 = 6$ inches. The value of the slot opening $s = 1$ inch. From Formula (**24**), the following *armature leakage path* reluctance is obtained:

$$r_2^{1}=\frac{0\ 313}{\frac{4\times 2.2\times 20\times 2.4}{1\times 14}+\frac{4\times 2.2\times 1.4\times 16.4}{14\times 2.4}+14+12}$$

$$= 51\times 10^{-4}. \textit{ Ans.}$$

This value is over 6 times larger than that of the air gap. The proportion between these two values has an important influence on the short circuit current, see Pars. **157** and **158**.

154. Effect of Leakage on Various Characteristics.—The leakage of the exciting field and that of the armature system are mentioned in Par. **136** as one of the elements which affect the inherent regulation.

The former shows its direct influence in the calculation of the open circuit characteristic, but the effect of the latter is more prominent on the short circuit current characteristic.

155. Leakage Factor.—The leakage factor, which is introduced in predetermining the calculation of the no-load characteristic, is defined as the ratio between the flux generated in the pole core inside the field coils and the flux which actually cuts the armature coils, which is useful for the generation of the E. M. F. in the armature winding.

The symbolical expression of this factor is:

$$\sigma = \frac{F_1}{F_2} = 1 + \frac{r_0}{r_1^{1}} + \frac{r_2}{r_1^{1}} + \frac{r_2}{r_2^{1}} \ldots\ldots\ldots \textbf{(25)}$$

The definition of the various symbols is given in Par. **138**.

The third and fourth items in the above equation are in most cases negligible, especially if the armature core is not highly saturated and for practical calculations the following simplified Equation (**26**), gives satisfactory results:

$$\sigma = 1 + \frac{r_0}{r_1^{1}}; \ldots\ldots\ldots\ldots\ldots\ldots \textbf{(26)}$$

and for the particular alternator which has 30 poles, a leakage factor of $\sigma = 1 + \frac{8}{24} = 1.33$ is obtained. That is to say: Out of every 133 lines generated in the field system only 100 will cut the armature coils.

156. Leakage Factor of Revolving Field Type Alternators.—In modern *revolving field* alternators the leakage factor lies within the limits of *1.15* to *1.5*, the latter value corresponding to machines with a large number of poles.

For the approximate calculation of leakage factor the following simple Formula (**27**), will be found useful:

$$\sigma = 1 + 6\frac{\delta \times d}{a \times m} \ldots\ldots\ldots\ldots\ldots (\mathbf{27})$$

157. Effect of Leakage on Short Circuit Current.—

The effect of leakage on the short circuit current reveals itself in the factor k_s, which in Par. **121** has been defined as the ratio between the ampere turns of the field system and the corresponding ampere turns of the short circuited armature.

The symbolical expression of this factor is:

$$k_s = 1 + \frac{r_0}{r_2^1} + \frac{r_1}{r_2^1} + \frac{r_1}{r_1^1}, \ldots\ldots\ldots (\mathbf{28})$$

but in most cases it will be sufficient to use the equation

$$k_s = 1 + \frac{r_0}{r_2^1} \ldots\ldots\ldots\ldots\ldots (\mathbf{29})$$

In the case of the alternator under discussion, Equation (**28**), gives:

$$k_s = 1 + \frac{8}{51} + \frac{1.65}{51} + \frac{1.65}{24} = 1.25.$$

158. Normal Value of Factor k_s.

—In modern alternators this factor has values which lie between *1.05* and *1.5.* A generator with a higher factor than that mentioned possesses excessive leakage, but it must be remembered, that the larger the number of poles the greater will k_s be for the same type of machine.

159. Demagnetizing Effect of Armature Ampere Turns.

—The demagnetizing effect of the armature ampere turns is the third factor which influences the voltage drop of an alternator; in fact, it is the decisive factor which determines the regulation.

Roughly speaking, the generator should not have a larger drop than $\frac{1}{3}$ of the open circuit voltage on an inductive load, $\cos \varphi = 0$, with normal excitation. Under these circumstances the excitation ampere turns for normal voltage must be three times greater than the ampere turns of the loaded armature, assuming that the leakage is zero.

160. Calculation of Armature Ampere Turns.—The following rules are employed to determine the armature ampere turns for armatures of different phase numbers.

Let T = the number of armature turns per phase, and
C = the current in each armature phase winding expressed in amperes.

Then the *back ampere turns* of a *single* phase generator are:

$$AT_b = 0.9 \times C \times T = A_2 \ldots\ldots\ldots\ldots (\mathbf{30})$$

The back ampere turns of a *two* phase alternator are expressed by:

$$AT_b = 1.41 \times C \times T = A_2 \ldots\ldots\ldots (\mathbf{31})$$

And the back ampere turns produced by a *three* phase alternator are:

$$AT_b = 2.12 \times C \times T = A_2 \ldots\ldots\ldots (\mathbf{32})$$

The coefficients of the above equations are based on a sinusoidal current wave form, but they may be applied in most cases without any alteration, as only a small correction is necessary.

161. Example 19.—In the case of a *single* phase generator having 672 turns, each carrying a normal current of 120 amperes, the theoretical number of *armature* ampere turns will be

$$A_2 = 0.9 \times 120 \times 672 = 72{,}576. \quad \textit{Ans.}$$

162. Example 20.—In a *two* phase generator, which has 64 slots each containing 12 conductors, the number of *turns per phase* will be $\frac{64 \times 12}{2 \times 2} = 192$; and if the armature current is equal to 400 amperes, the value of the back ampere turns will be

$$A_2 = 1.41 \times 400 \times 192 = 108{,}290. \quad \textit{Ans.}$$

163. Example 21.—If a *three* phase generator has 924 conductors on its armature, the total number of turns will be $\frac{924}{2} = 462$, and the number of *turns per phase* $\frac{462}{3} = 154$. Assuming a current of 90 amperes in each phase, the total number of *armature* ampere turns will be

$$A_2 = 2.12 \times 90 \times 154 = 29{,}260. \quad \textit{Ans.}$$

164. Effect of Armature Ampere Turns on Inductive Load.—In the case of an alternator with an inductive load $\cos \varphi = 0$, the armature ampere turns counteract the effect of the field ampere turns, assuming that the magnetic leakage is nil.

It may be stated, however, that a fractional part of the total armature ampere turns does not affect the field at all, but simply provides the usual armature leakage lines of flux.

165. Calculation of Open Circuit Characteristic.—The calculation of the no-load characteristic of alternating current generators is exactly the same as that of continuous current dynamos. It is necessary to determine the number of ampere turns which are required to drive a certain number of lines of flux through the magnetic circuit of the machine, and if this is carried out for different values of flux, and the latter plotted in terms of their corresponding ampere turns, it will give the magnetizing curve of the magnetic circuit, which is, at the same time, the open circuit or E. M. F. characteristic. This result is due to the fact, that the E. M. F. of the armature of an alternator is directly proportional to the flux which cuts the armature coils, as expressed in the equation:

$$E = \frac{k \times n \times Z \times F_2}{10^8}, \ldots\ldots\ldots\ldots (33)$$

where, k is the form factor characterizing the wave form of the E. M. F. and is more or less constant for any degree of saturation;

n, the number of cycles per second; and

Z, represents the number of armature conductors per phase.

For any particular alternator these values are constant; consequently the E. M. F. of the armature depends only on the number of useful magnetic-lines F_2.

166. Useful Flux.—Further, it may be stated, that the ampere turns required to generate a useful flux of F_2 per pole are expressed in the equation:

$$A_1 = r_1 \times F_2 \times \sigma + r_0 \times F_2 + r_2 \times F_2 \ldots . (34)$$

where, A_1 is the number of ampere turns or the E. M. F. of one pole,

r, represents the magnetic resistances of the various paths;

F_2 the useful flux, which we assume is equal to that passing through the air gap and armature system;

$F_2 \times \sigma$, the value of the flux originated in the field system, from which we may assume that it is constant for all parts of the field path; and

σ, the leakage factor which indicates the ratio of the field flux to that of the armature.

167. Proper Determination of No-Load Characteristic.—From Formula (**34**), it follows, that the proper determination of the magnetizing or no-load characteristic depends on the application of the correct magnetizing data for the iron material employed.

This magnetizing data should give the different values of permeability for the various magnetic densities, or the number of necessary ampere turns per inch of iron length; and further it must be noted, that the correct value of the leakage factor, the values of the different sectional areas of the magnetic circuit and the lengths of the various paths should be fixed.

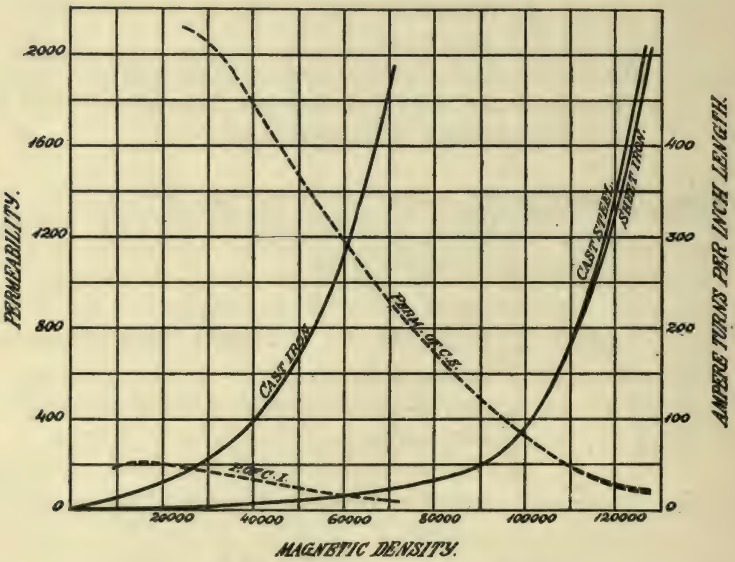


FIG. 46.—MAGNETIZATION CURVES.

Equation (**33**), shows, that in order to determine the E. M. F. curve, a knowledge of the form factor is required, provided that the values n and Z are given.

168. Magnetization Curves.—Magnetization curves ror different qualities of iron are given in Fig. 46. These curves hold good for the examples of machine design under discussion, enabling the calculated results to be checked by those of the actual tests.

In Fig. 46, two sets of curves are given, one of which indicates the values of the permeabilities for various magnetic densities; and the other set shows how many ampere turns are required to drive the magnetic lines of flux, corresponding to the density, through a path length of *one* inch. By the application of the latter set of curves, the calculation of the necessary ampere turns is greatly facilitated.

169. Example 22.—Assume, for instance, that the length of a pole core is 8 inches and the section of the core 88 square inches. Then for a flux of 8.3×10^6 the density in the section will be $\frac{8.3 \times 10^6}{88} = 94{,}000$ lines per square inch and the corresponding number of ampere turns 70, provided that the material of the core is sheet iron.

The ampere turns required in this particular case for the 8 inch pole, are $8 \times 70 = 560$.

170. Correct Leakage Factor.—The second condition in the proper determination of the no-load characteristic is to calculate the correct leakage factor. This may be accomplished by the calculation indicated in Par. **155**.

171. Estimation of Sectional Areas.—The proper estimation of the various sectional areas and the length of magnetic path, is based on the data of average permissible densities, on condition of the economical use of material and the provision of the necessary space for the copper winding.

172. Assumption of Form Factor.—The correct assumption of the form factor is an important matter, because its value varies as much as 50% and more, for the different kinds of winding on the armature.

For the continuous current dynamo, the factor k is always equal to 1, but in alternating current machines, where the effective value of the current is different from that of the mean current, the form factor varies as above stated.

When the wave form of the E. M. F. is sinusoidal, then the factor $k = 2.22$; for a rectangular wave form $k = 2$; and for a wave composed by two inverted quarter sine curves, the form factor $k = 2.62$.

173. Resultant Wave Form.—The resultant wave form of the E. M. F. of a generator depends on the kind of winding employed, that is, on the space and distribution of the armature coils and on the ratio between the pole arc and

TABLE 14.—FORM FACTOR "k" FOR DIFFERENT WINDINGS.

Columns.		1			2		3		4	
Number of slots per pole and phase......		Electrically equivalent to a smooth winding....			3		2		1	
With reference to Fig.					49. 55.	52. 58.	48. 54.	51 57	47. 53.	50. 56.
Number of phases.....		1	2	3	1and2	1and3	1and2	1and3	1 and 2 and 3	
Ratio of coil breadth to pole pitch..		1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{1}{4}$	$\frac{1}{6}$	0	
Ratio of pole arc to pole pitch.	$\frac{1}{2}$	1.64	2.32	2.50	2.36	2.54	2.45	2.59	2.83	
	$\frac{2}{3}$	1.49	2.13	2.23	2.16	2.26	2.18	2.30	2.46	
	$\frac{4}{5}$	1.29	1.82	1.96	1.98	2.10	2.02	2 12	2 23	
	1	1 16	1 64	1 76	1.68	1.80	1.72	1 82	2 00	

the pole pitch. Further, secondary influences are: the saturation of the teeth and hysteresis in the same. The better the coils are distributed, the nearer will the wave form be to that of a sine curve.

174. Form Factor with Long Coils.—For windings with long coils as now adopted, Table **14** gives the different values of the form factor.

The definition of a long coil is, that the mean distance between the sides of a coil shall be exactly, or approximately, equal to the distance between successive poles, which is: $a + n \doteq \tau$, (see Fig. 42).

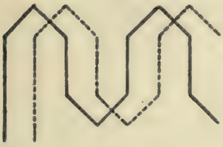


Fig. 47.

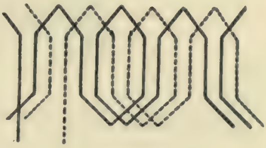


Fig. 48.

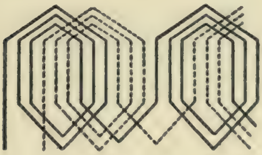


Fig. 49.

Figs. 47, 48 and 49.—Two-Phase Windings.

Column 1 of Table **14** represents the form factor values for the symmetrical bar winding, with so many slots per pole and phase that the winding is electrically equivalent to a smooth winding.

Column 2 gives the data corresponding to the two and three phase windings of the Figs. 47 to 52. The same values also hold good for a single phase armature, Figs. 53 to 58, providing that it is obtained by omitting the phase winding of Figs. 47 to 49 or leaving empty the slots of the two phases in the Figs. 50 to 52.

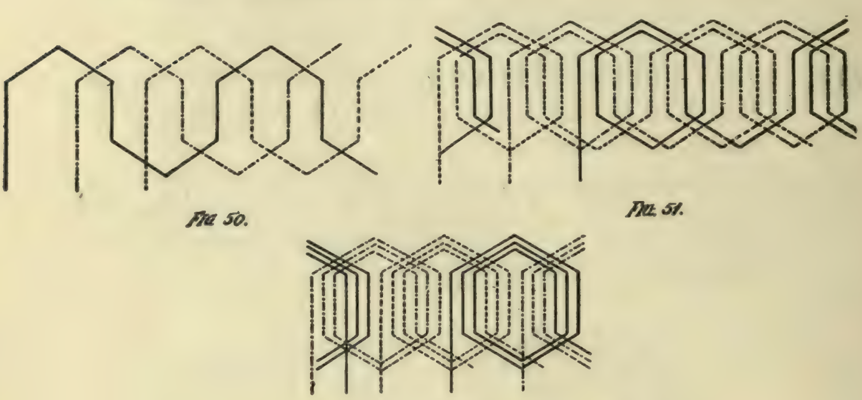


Fig. 50.

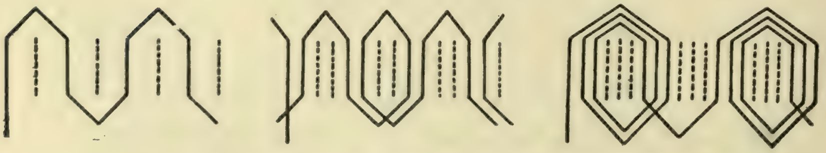
Fig. 51.

Fig. 52.

FIGS. 50, 51 AND 52.—THREE-PHASE WINDINGS.

175. Ratio Between Coil Breadth and Pole Pitch.—

For illustrating the meaning of *ratio between coil breadth and pole pitch,* take for instance, the value of $\frac{2}{9}$ column 2, Table **14**, which is obtained by measuring the pole pitch with the 9 slot pitches and the coil breadth by the 2 slot pitches, which are located between the 3 coils of one side.



FIGS. 53, 54 AND 55.—SINGLE-PHASE WINDINGS.

176. Ratio Between Pole Arc and Pole Pitch.—As regards the *ratio of pole arc to pole pitch,* it should be noted that the values $\frac{1}{2}$, $\frac{2}{3}$, Table **14**, are applicable to the alternate poles of a revolving field type alternator, and $\frac{4}{5}$ and 1 belong to the equipolar magnet system of the inductor type generator.

The data in column 4 is based on the supposition, that the width of the slot winding and coil breadth ratio is zero. This, however, does not comply with the actual case, but still the data is sufficient for practical purposes.

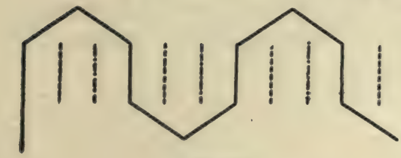


Fig. 56.

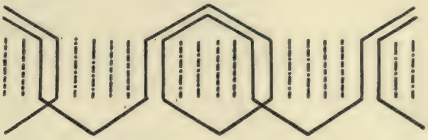


Fig. 57.

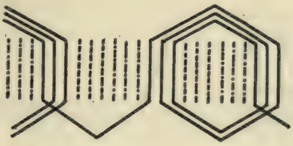


Fig. 58.

FIGS. 56, 57 AND 58.—SINGLE-PHASE WINDINGS.

The somewhat lengthy method of determining, graphically, the form of magnetic field from which the E. M. F. wave form is derived, is only of importance in such a case in which the intention of a designer is to utilize the material to the utmost limit, which of course leaves no margin for discrepancies.

It should be intimated at this point, that it is not desirable to drive the design up to the limit of practical calculations.

177. Reasonable Pole Arc Ratio.—Table **14** indicates clearly, that the smaller the pole arc ratio, the larger the form factor; it is misleading to conclude that it is favorable to work with small pole arcs. Generally speaking, any decrease in the pole arc effects an increase in the form factor and also improves the leakage conditions, but otherwise it diminishes the area of the air section, which is larger than the increase of the form factor.

In practice it is found that it is best to keep the pole arc ratio at about $\frac{2}{3}$ for alternate poles and at about 1 for equipole machines.

178. Example 23.—A 375 KVA. revolving field type, slow speed, two phase alternator, with 64 poles, is dimensioned as indicated in Figs. 59 and 60. The normal phase voltage is 3,000, at a frequency of 50. The armature contains 256 slots each having 15 conductors.

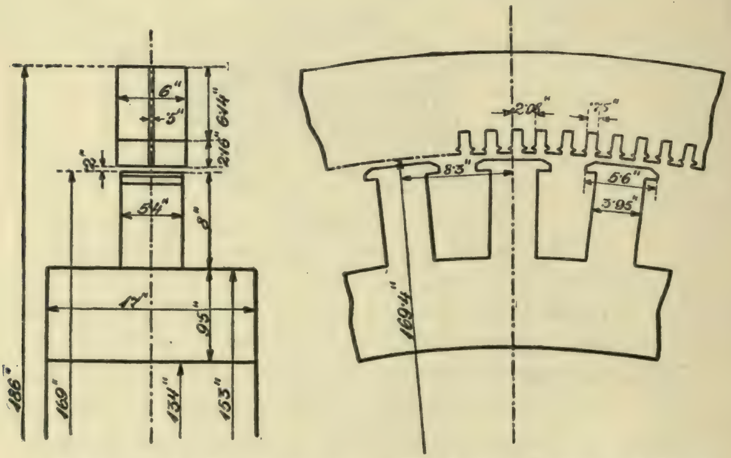


FIG. 59.—375 KVA., 3,000 VOLT, 93¾ REVS., 50-CYCLE, 2-PHASE ALTERNATOR.

NO-LOAD CHARACTERISTIC: In order to determine the no-load characteristic, the necessary ampere turns should be calculated for four different degrees of saturation corresponding to 3,500, 3,000, 2,500 and 2,000 volts terminal pressure.

FORM FACTOR: By means of Formula (**33**), the different values of the useful flux are obtained, but first of all, the value of the form factor must be ascertained.

In this particular case the number of slots per pole is 4 and the number of slot pitches between the coils of one side is 1. Consequently the coil breadth ratio is $\frac{1}{4}$; the pole arc is equal to 5; and the pole pitch to 8.3 inches; so that the pole arc ratio is 0.6 and from the third column of Table **14**, a form factor of $k = 2.34$ is obtained by interpolation.

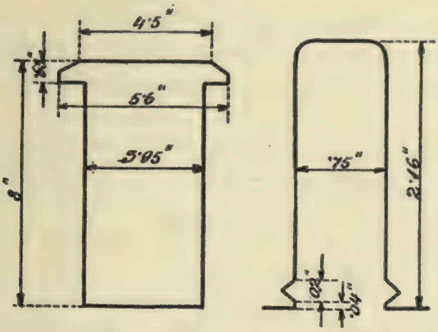


FIG. 60.—POLE PIECE AND SLOT OF THE 375 KVA., 90¾ REVS., 2-PHASE ALTERNATOR.

Substituting these values in Formula (**33**), we have:

$$10^8 \times 3{,}000 = 2.34 \times 50 \times 1{,}920 \times F_2,$$

because the frequency is 50 and the number of conductors per phase, $128 \times 15 = 1{,}920$.

USEFUL ARMATURE FLUX: With the above data it is found, that for the generation of the different E. M. F.'s a useful armature flux, F_2, is required, as follows:

$$F_2 = 1.56 \times 10^6 \text{ lines for } 3{,}500 \text{ volts,}$$
$$F_2 = 1.34 \times 10^6 \text{ lines for } 3{,}000 \text{ volts,}$$
$$F_2 = 1.12 \times 10^6 \text{ lines for } 2{,}500 \text{ volts and}$$
$$F_2 = 0.9 \times 10^6 \text{ lines for } 2{,}000 \text{ volts.}$$

LEAKAGE FACTOR: In order to complete the required data it is necessary to calculate the leakage factor.

On referring to the magnetic circuit, Fig. 42, in connection with the dimensions given in Figs. 59 and 60, we have:

$a = 5.6$ inches; $r = 1.33$ inches; $l = 5.5$ inches; $o = 2.08$ inches; $\delta = 0.2$ inches; $u = 0.2$ inches; $s = 0.75$ inches; $c = 0.63$ inches; $f = 5.4$ inches; $n = 2.7$ inches; $d = 7.37$ inches; $m = 4$ inches; and $b = 3.95$ inches.

Hence the air gap reluctance from Formula (**20**) will be

$$r_0 = \frac{0.313}{\frac{5.6 \times 1.33 \times 5\ 5}{2.08 \times 0.2} + \frac{5.5 \times 5\ 6 \times (0.2 + 0.38)}{2.08 \times 0.4}} = \frac{0.313}{98 + 21.5} = \frac{26}{10^4};$$

and from Formula (**23**), a value for the reluctance of the field leakage path of:

$$r_1{}^1 = \frac{0.313}{\frac{4 \times 0.63 \times 5.4}{2.7} + \frac{4 \times 7.37 \times 5.4}{4} + \frac{4 \times 3\ 95 \times 7.37}{7.9}} = \frac{0.313}{5 + 40 + 14} = \frac{53}{10^4}$$

is found.

Consequently, in accordance with Formula (**26**), a leakage factor σ of 1.49 is obtained.

If the two other items of Formula (**25**) are taken into consideration, a further 6 per cent of 0.49 must be added to σ, thus making $\sigma = 1.52$.

Assuming an average constant value for the above degrees of saturation, it follows that the field system will carry a flux of

2.37×10^6 lines for an E. M. F. of 3,500 volts,
2.04×10^6 lines for an E. M. F. of 3,000 volts,
1.70×10^6 lines for an E. M. F. of 2,500 volts, and
1.36×10^6 lines for an E. M. F. of 2,000 volts.

FIELD AMPERE TURNS: By means of Formula (**34**), the necessary number of field ampere turns may be calculated, by fixing the values of the length of the different paths and by taking from the magnetizing curves of Fig. 46, the values of the ampere turns per unit length of the various paths.

RELUCTANCE OF WHEEL RIM: Take for example the case where the useful flux is equal to 1.34×10^6 lines; then the magnetic density in the wheel rim will be $\frac{2.04 \times 10^6}{2 \times 160}$ lines per square inch, because the sectional area is equal to 160 square inches for which the induction is 6,400, provided that the rim material is ordinary cast iron; then the ampere turns required to overcome the resistance of one inch length is equal to 10.

As the total length of the rim path e, belonging to one pole is 6 inches, the total ampere turns for the rim are equal to $10 \times 6 = 60$ per pole.

RELUCTANCE OF POLE CORE: The section of the pole core is $5.4 \times 3.95 \times 0.96 = 20.5$ square inches, and so the magnetic density: $\frac{2.04 \times 10^6}{20.5} = 100{,}000$ lines per square inch (approx.).

The material being sheet iron, the necessary ampere turns per one inch length of path = 90, according to the data of Fig. 46.

As the height d, of the pole core = 7.37 inches, the total ampere turns belonging to this part of the magnetic circuit $= 90 \times 7.37 = 663$.

RELUCTANCE OF TEETH: The teeth opposite to one pole shoe face offer a section of $\frac{a}{o} \times r \times l \times 0.9 = \frac{5.6}{2.08} \times 1.33 \times 5.5 \times 0.9 = 17.5$ square inches, for the flow of the useful flux of 1.34×10^6 lines; therefore the magnetic density is $\frac{1.34 \times 10^6}{17.5} = 77{,}000$; and as the material is of sheet iron, the ampere turns per unit length of path are equal to 30.

The height i of a tooth being 2.16 inches, the toothed path requires a M. M. F. of $2.16 \times 30 = 65$ ampere turns.

It may be pointed out at this stage, that in the case of a small armature bore where the height of the teeth is a large percentage of same, the sectional area has to be calculated as the mean value of the top and bottom sections of the teeth. In this particular case the difference is insignificant.

ARMATURE CORE RELUCTANCE: The armature core offers a section of $6.14 \times 5.5 \times .9 = 30$ square inches and a length v of 5.5 inches.

The magnetic density in the sheet iron is equal to $\frac{1.34 \times 10^6}{2 \times 30}$ $= 22{,}400$ lines per square inch and the corresponding ampere turns per unit length are 4, making the total number for the armature core equal to $5.5 \times 4 = 22$ per pole.

AIR GAP RELUCTANCE: In calculating the leakage factor, the air gap reluctance has been already found equal to $r_0 = \frac{26}{10^4}$ and from which $r_0 \times F_2 = \frac{26}{10^4} \times 1.34 \times 10^6 =$ 3,480 ampere turns.

TOTAL AMPERE TURNS PER POLE: The five distinct magnetic paths require, in all, a total number of ampere turns amounting to 4,310 per pole, when the generated E. M. F. of the armature is 3,000 volts.

By following up the same course of calculation for three other degrees of saturation, the curve of the open circuit characteristic is obtained.

The systematic arrangement of the various data and results, Table **15**, will be found very useful, as indicated in the present example.

CHARACTERISTIC RATIO: In Fig. 61, the E. M. F. is plotted in terms of the corresponding ampere turns. The following remarks on the form of this open circuit characteristic are based on the calculation of the apparent magnetic resistance curve.

TABLE 15.

E. M. F.				3 500		3 000		2,500		2 000	
Armature Flux.				1.56×10^6		1.34×10^6		1.12×10^6		0.9×10^3	
Field Flux.				2.37×10^6		2.04×10^6		1.70×10^6		1.36×10^3	
Material and Sectional Area of:	Wheel Rim.	Cast Iron. 160 Sq. Ins.	Magnetic Densities and Corresponding Ampere Turns per Inch Length.	7,460	11.5	6,400	10	5,330	8	4.260	6.5
	Pole Core.	0 04″ Sheet. 20.5 Sq. Ins.		116.000	240	100,000	90	83,250	40	66,600	22
	Teeth.	0.02″ Sheet. 17.5 Sq. Ins.		90,000	50	77,000	30	64,100	21	51,300	13
	Armature Core.	0.02″ Sheet 30 Sq. Ins.		26,100	4.6	22,400	4	18,700	3.4	15,000	2.6
Length of Magnetic Paths in Inches.	Wheel Rim.	6	Ampere Turns of the Paths.	69		60		48		39	
	Pole Core.	7.37		1,760		663		295		162	
	Teeth.	2.16		108		65		45		28	
	Armature Core.	5.5		25		22		19		14	
r_0		$\frac{26}{10^4}$		4,060		3,500		2 920		2,340	
Total Ampere Turns per Pole.				6,022		4,310		3 327		2,583	

The values of these reluctances are indicated by:

$$\frac{6{,}020}{1.56 \times 10^6} = \frac{38.6}{10^4}, \text{ corresponding to an excitation of 6,020 ampere turns,}$$

$$\frac{4{,}310}{1.34 \times 10^6} = \frac{32.1}{10^4}, \text{ corresponding to an excitation of 4,310 ampere turns,}$$

$$\frac{3{,}325}{1.12 \times 10^6} = \frac{29.6}{10^4}, \text{ corresponding to an excitation of 3,325 ampere turns, and}$$

$$\frac{2{,}585}{0.9 \times 10^6} = \frac{28.9}{10^4}, \text{ corresponding to an excitation of 2,585 ampere turns.}$$

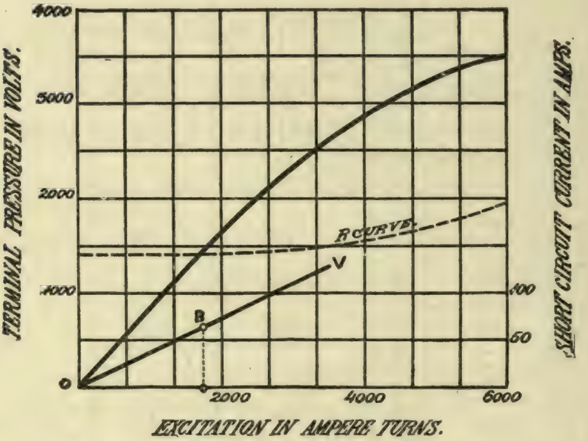


FIG. 61.—CHARACTERISTICS OF A 375 KVA. 2-PHASE ALTERNATOR.

The curve resulting herefrom gives a characteristic ratio $\frac{\overline{R}^2}{R_s^2}$ which is lower than that of a standard alternator, where it is about 1.6.

The greatest iron contribution to the magnetic reluctance of the circuit is the wheel rim and pole core, where the high saturation does not affect the amount of the iron losses, as practically all these losses are located in the armature core, where the magnetization is always varying.

AMPERE TURNS FOR ENTIRE POLE SYSTEM: The values of ampere turns previously found are for one pole only; therefore, for the entire pole system the total value will be equal to $64 \times 4{,}310 = 275{,}840$ ampere turns for a voltage of 3,000 at the terminals.

179. Calculation of Short Circuit Characteristic.—In Par. **121**, it has been shown that the short circuit characteristic is represented by the equation:

$$A_{1s} = A_2 \times k_s$$

where,

$$k_s = 1 + \frac{r_0}{r^1_2} + \frac{r_1}{r^1_2} + \frac{r_1}{r^1_1}.$$

This factor for a wide range of excitation remains constant; therefore the characteristic is a straight line and its determination is identical with the calculation of the factor k_s.

180. Example 24.—For a practical example, the data of Par. **178** may be used, from which it is necessary to calculate the values of r_1, r_0, r^1_2 and r^1_1 by means of Equations (**19**), (**20**), (**23**) and (**24**).

SATURATION OF MAGNETIC CIRCUIT: As already pointed out, the saturation of the magnet circuit with a short circuited armature, is very low and corresponds only to the leakage flux. In consequence of this low saturation, the values of the permeability in the pole core as well as in the wheel rim, will have comparatively high values, as proved by a glance at the permeability curves of Fig. 46. With these large permeability values, the items $\frac{r_1}{r^1_2}$ and $\frac{r_1}{r^1_1}$ in the expression of k_s are entirely negligible; therefore k_s may equal $1 + \frac{r_0}{r^1}$.

For this particular case r_0 has been already determined and found to be equal to $\frac{26}{10^4} = r_0$.

Armature Leakage Reluctance: The expression of the armature leakage reluctance is

$$r_2^1 = \frac{0.313}{\frac{4 \times i \times l \times o}{s(n+a)} + \frac{4 \times i \times r(a+n+o)}{(a+n)o} + a + n + 2l_1},$$

which gives in the present example a value of

$$r_2^1 = \frac{0.313}{\frac{4 \times 2.16 \times 5.5 \times 2.08}{0.75 \times 8.3} + \frac{4 \times 2.16 \times 1.33(8.3+2.08)}{8.3 \times 2.08} + 8.3 + 8.7}$$

$$= \frac{0.313}{16+7+17} = \frac{78.5}{10^4},$$

from which the factor k_s is equal to

$$k_s = 1 + \frac{26}{78.5} = 1.33;$$

that is, each 1,000 ampere turns of the field produce $\frac{1,000}{1.33} = 750$ ampere turns on the short circuited armature.

Useful Rules: If the number of armature turns are given, it is very simple to obtain the value of the short circuit current, or, if a certain short circuit current be given, to calculate the corresponding field excitation.

Ampere Turns per Pole: In this particular case, the normal armature current 62.5 amperes would produce a M. M. F. of 1.41 × 62.5 × 64 × 15 = 84,500 total ampere turns; this requires, on short circuiting, a total field M. M. F. of 1.33 × 84,500 = 112,000, or $\frac{112.000}{64} = 1,75$ ampere turns per pole.

Short Circuit Characteristic: If we now fix the point B, by erecting the normal armature current as an ordinate, from the corresponding field ampere turns as abscissa and draw a line through *B* and the zero point, this straight line *OV*, will represent the short circuit characteristic with satisfactory exactness. This operation has been performed in Fig. 61, giving the characteristic of the 375 KVA. two phase alternator.

RATIO OF ARMATURE CURRENTS: In conclusion it is interesting to state that, for this machine, the ratio between the normal armature current and the current of the short circuited armature, when the excitation corresponds to normal open circuit voltage is $\frac{154}{62.5}$ which is equal to 2.46, a good commercial value.

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THE DESIGN OF ALTERNATING GENERATORS AND SYNCHRONOUS MOTORS.

SUMMARY OF PROBLEMS IN DESIGN.

181. Problems in Design.—The principal problems in design are:

1, regulation;
2, losses or efficiencies;
3, temperature rise;
4, economical use of the different materials; and
5, the method of arranging suitable space for the windings with regard to mechanical safety.

All these problems are more or less connected with each other and their best combination is specified in Pars. **12** to **19**.

Practice has approved certain compromises in the determination of the different items, in order to obtain successful designs.

182. Regulation and Efficiency.—The compromise between the items 1 and 4 may be characterized principally by the proper choice of the armature ampere turns, or of the total magnetic flux $2p \times F_2$ corresponding to the normal open circuit pressure. The former, as the *copper source* of the alternator, affects the amount of copper required; and the latter, the *iron source* of the alternator, directly influences the amount of iron material.

It is obvious, that a certain size of alternator with certain qualities may be obtained by different designs, such as a design having more iron and less copper winding, or one resulting in an ample application of armature and field copper, but of reduced iron material.

183. The Use of a Large Number of Armature Ampere Turns.—Take for instance a particular case where an inductive cos $\varphi = 0$ voltage drop of 25% is specified, which, as already known, involves a certain ratio between the numbers of the armature and field ampere turns.

A large number of armature ampere turns may be chosen, resulting in a considerable amount of field winding. The fundamental Equation (**33**) indicates clearly, that in this particular case the number of magnetic lines F_2, passing through the iron body, will proportionally decrease, resulting in a decrease of the volume and section of the iron.

184. The Use of a Small Number of Armature Ampere Turns.—If an armature winding with a small number of turns is taken, then the turns on the field are accordingly smaller, but the amount of iron must be large in order to carry the necessary flux, which increases as the turns of the armature winding decrease.

185. The Influence of the Length of Mean Turn.—In conclusion, it should be pointed out that the reduction of one material does not effect a proportional increase of the other. For instance in a certain design where the armature turns are reduced to one-half the value, the copper in this design will not fall to one-half the amount, because with the increasing dimensions of the iron, the mean length of a turn is also increased.

186. Minimum Material Costs.—For certain specified conditions a satisfactory division of the *copper* and *iron sources* will always be found, so that the resulting copper material with its high price and the iron with its lower price, will give the minimum material costs.

Of course, these minimum costs will be affected by many other details, such as current densities, etc., but the proper choice of the total flux and armature turns for a certain regulation, is the principal factor of the economical application of material.

187. Magnetic Flux and Commercial Regulation.—Fig. 62 indicates the different values of the total flux

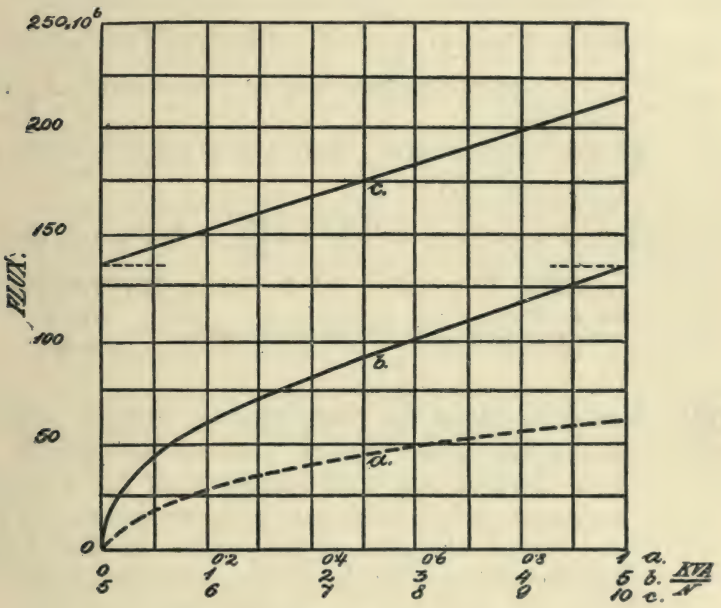

FIG. 62.—AVERAGE FLUX VALUES.

$2p \times F_2$ in terms of $\frac{KVA.}{N}$, that is, in terms of the capacity of the alternator *per unit revolution*.

This data leads to the most favorable division of the *copper* and *iron sources* as regards commercial regulation, as well as the most economical distribution of material.

If a higher voltage drop than reasonable is permitted, then the total flux may be less than that indicated in Fig. 62.

188. Example 25.—A 300 KVA. alternator, running at a speed of 100 r.p.m. and generating an E.M.F. at 50 cycles, should, for the normal voltage, have a total flux corresponding to $\frac{300}{100} = 3 = \frac{KVA.}{N}$; that is, it has to be about 100×10^6 lines. The number of poles being 60, a useful flux per pole of $\frac{100}{60} \times 10^6 = 1.66 \times 10^6$ will be required if a reasonable voltage drop and an economical design is desirable.

As another illustration, take a 400 KVA., 60 cycles, 600 r.p.m. machine:

In this case the ratio $\frac{KVA.}{N} = \frac{400}{600} = 0.666$, and the corresponding flux value is $F_2 \times 2p = 52 \times 10^6$ lines; or $\frac{52 \times 10^6}{12} = 4.33 \times 10^6$ lines per pole.

189. Reliable Data for Alternator Design.—The data of Fig. 62, together with the fundamental Equation (**33**), offer the best and most reliable basis for a successful alternator design, which can be further assisted by proper and skilful calculation of the details. In Par. **165**, the fundamental equation has been given in the form:

$$E = \frac{k \times n \times Z \times F_2}{10^8}.$$

This can be advantageously written in another form, by multiplying both sides of the equation with the number of phases *m* and with the normal current in amperes, from which,

$$m\times E\times C=\frac{k\times m\times n\times Z\times C\times F_2}{10^8}=\frac{k}{10^8}\times\frac{N\times p}{60}\times m\times Z\times C\times F_2,$$

is obtained, where the value of the frequency n is replaced by the expression $\frac{N \times p}{60}$.

Finally, since $m \times E \times C = KVA. \times 10^3$, we have:

$$\frac{KVA.}{N} = m \times Z \times C \times 2p \times F_2 \times \frac{k}{120 \times 10^{11}} \quad ..(35)$$

190. Choice of Armature Flux.—For alternators with similar windings and the same pole arc ratios, the form factor is constant and so there is obtained the expression:

$$\frac{KVA.}{N} = Constant \times m \times Z \times C \times 2p \times F_2 \quad ..(36)$$

This equation indicates that with the choice of the total armature flux, the number of the armature conductors is fixed and it is a simple matter to follow up the right course of calculation for other compromises required.

In Example **25** of Par. **188**, Equation (**35**) indicates a value for the armature ampere conductors, where k is assumed to be 2.2,

$$3 = m \times Z \times C \times 100 \times 10^6 \, \frac{2.2}{120 \times 10^{11}}, \text{ and } m \times Z \times C = 163{,}600.$$

Or if the machine is three phase, with a phase voltage of 2,000, then the current $C = 50$ amperes, $m = 3$, and the number of armature conductors per phase $= \frac{163{,}600}{3 \times 50} = 1{,}087$.

191. Determination of Bore.—For the determination of the most suitable bore of the armature, the data given in Fig. 63 forms a sound basis to work upon, and indicates the number of armature ampere conductors per one inch length of the periphery.

This peripheral density is defined as

$$(Z\,C) = m \times Z \times \frac{C}{D \times 3.14} \quad \ldots\ldots\ldots (37)$$

where $(Z\,C)$ is the symbol of peripheral density; $m =$ the number of phases; $Z =$ the number of conductors per phase of the armature; and $C =$ the current in a phase winding.

The data of the ampere conductors per inch periphery, in terms of the machine capacity in KVA., indicates a compromise between the items 1 and 3 in Par. **181**, as the choice of the diameter according to the peripheral density takes into account the question of the regulation, the provision of the necessary cooling surface, and the winding space.

192. Peripheral Densities for Polyphase Machines.—Fig. 63 gives good average values for 50 cycle, low and medium tension polyphase alternators. For 25 cycle machines, the peripheral densities may be about 20% higher, and for those of a high tension generator about 20% lower. The average peripheral densities of single phase alternators are approximately 80% of the figures given for polyphase machines.

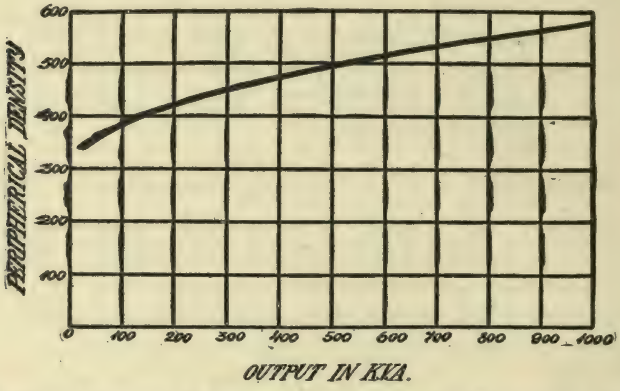

Fig. 63.—Average Peripheral Densities of Standard Polyphase Alternators.

193. Example 26.—From Par. **190**, the 300 KVA., 100 r.p.m. alternator, has a total armature ampere conductor value of 163,600. Assuming the peripheral density corresponding to a generator of 300 KVA. capacity, which is 450, Equation (**37**) gives an armature bore of

$$D = \frac{163{,}600}{450 \times 3.14} = 114 \text{ inches.}$$

194. Peripheral Speed.—It is always advisable to check the diameter by calculating the peripheral speed of the magnet wheel, which is equal to

$$V = D_1 \times 3.14 \times \frac{N}{12} \ldots\ldots\ldots\ldots \textbf{(38)}$$

where D_1 = the external diameter of the wheel in inches;

N = the number of revolutions per minute;

and V = the peripheral speed in feet per minute.

The value of the peripheral speed indicates the importance of safe mechanical dimensions. This data is used only in special cases for guidance in the choice of the diameter, because nowadays it is not found difficult to cope with peripheral speeds as high as 10,000 feet per minute, and even more. The peripheral speeds of standard alternators vary only within small limits, and on the average it is usually 4,500 to 6,000 feet per minute.

195. Effective Iron Length.—For the determination of the effective iron length of the armature, it is necessary to be guided by the data of average tooth densities for different periodicities, which represent a compromise regarding the items 2 and 4 of Par. **181**.

The lower the specified efficiency, the higher may the magnetic density be driven, resulting in the length of the machine becoming smaller.

196. Proportions of Alternators.—In the design of electrical machines it is customary to apply the rule

$$KVA \times Constant = D^2 \times L \times N \text{.........} \mathbf{(39)}$$

as a guide for the approximately correct proportioning of the alternator.

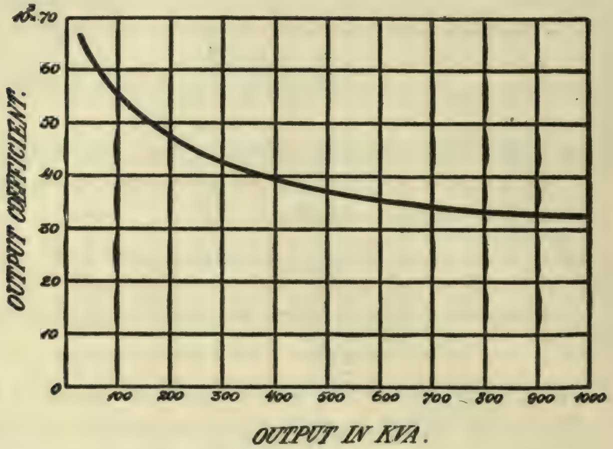

FIG. 64.—OUTPUT COEFFICIENTS OF STANDARD POLYPHASE ALTERNATORS.

Fig. 64 indicates the values of the constant or factor *f* for various sizes of generators.

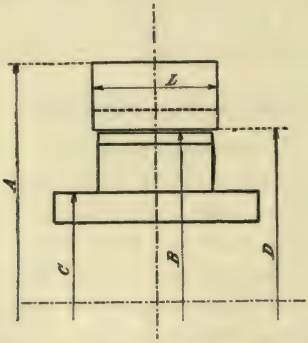

FIG. 65.—LEADING DIMENSIONS OF ALTERNATORS.

Table **16**, applied to Fig. 65, gives the leading dimensions of standard 50 cycle polyphase alternators, together with the characteristics, peripheral speed and factor *f*.

The output of the various machines is about 75% of the figures indicated in Table **16**, if they are to supply single phase current.

TABLE 16.—LEADING DIMENSIONS OF STANDARD 50-CYCLE POLYPHASE ALTERNATORS.

K.V.A.	R.P.M.	Number of Poles.	Number of Slots.	*V*, Vel. in Ft. per Min.	*f*, Output Coeffic.	Dimensions in Inches.				
						A	B	C	D	L
25	1,000	6	36	4,200	72×10^3	22	15.84	8	16	7.00
50	1,000	6	36	5.200	64 "	27	19.80	10	20	8 00
100	750	8	48	5,300	52 "	35	26.76	16	27	9.50
200	600	10	60	5,900	48 "	50	37.68	23	38	11 00
300	430	14	84	5,900	42.5 "	76	51.60	37	52	11.00
500	375	16	96	6.600	39 "	82	66.52	51	67	11.50
750	300	20	120	6 600	34 5 "	102	83.45	68	84	12.00
1,000	250	24	144	6,900	32.5 "	120	101.40	85	102	12.50

197. Output Constant.—Table **17** gives the outputs of standard alternators for low, medium and high tension. The reduction in the output of high tension machines is

TABLE 17.—OUTPUTS FOR STANDARD ALTERNATORS FOR LOW, MEDIUM AND HIGH TENSIONS.

Type.	Low and Medium Tension.		High Tension.	
	Volts.	Output.	Volts.	Output.
1	500	10 KVA.	1 000	8 KVA.
2	1.000	20 "	2,000	15 "
3	3,000	50 "	6.000	40 "
4	3.000	100 "	6.000	80 "
5	3 000	200 "	6,000	160 "
6	5,000	300 "	10,000	220 "
7	5,000	500 "	10,000	400 "
8	5,000	750 "	10,000	550 "
9	5,000	1,000 "	10,000	800 "

directly connected with the reduced winding space inside the slot, which has to take more insulation material.

The skill of the designer and the quality of the insulation material considerably affect the output constant.

198. The Greatest Iron Reluctance.—It should be noted that the greatest iron reluctance should be placed in the *field iron,* as such a part does not contribute any noticeable amount to the losses, but gives the regulation a favorable knee or bend on the open circuit characteristic. This rule represents a compromise between the conditions 1 and 2, Par. **181**.

199. Choice of Density.—The conditions 2, 3, 4 and 5 are more or less affected by the choice of the current and magnetic densities, for which the average values are given in Pars. **88**, **89** and **95**.

200. Dimensions of Pole Arc Ratio.—It is necessary to bear in mind that the conditions 1 and 4 are both affected by the ratio between the pole arc and pole pitch, for with a very large pole arc, the leakage becomes great and with a very small pole arc the economy of the design is diminished.

For alternate pole alternators it has been found that a *pole arc ratio of* $\frac{2}{3}$ is about the most suitable value.

201. Details of Slots.—In designing the slots care should be taken that the slot insulation and the coil should be designed so as to avoid driving the tooth saturation too high, or making the width of the tooth too small, so introducing mechanical weakness.

Once the leading dimensions are fixed, the choice of the right number and form of slots should receive the consideration of the designer.

With regard to the amount of leakage, it is advisable to keep the ratio of slot depth to slot width *within* the limit of *3* to *1.*

202. Height of Pole Cores.—The next investigation, is to see if the field winding can be conveniently placed in the available space, especially on the bottom periphery. It is well to consider that very high pole cores are mechanically weak, besides possessing magnetic disadvantages due to the increase of the leakage factor. On the other hand, in order to obtain a low pole core, it is necessary to use a magnet coil of large winding depth, which should, under any circumstances, not exceed 2 inches. The latter condition is based on the experience that coils with a great winding depth are liable to break down, because the cooling of the inner turns is imperfect, producing a carbonizing of the insulation material.

203. Temperature Rise.—The temperature rise presents itself as an important item with regard to the reliable working of the generator. In a good design it is easy to arrange the electrical details, so that the temperature will not exceed the permissible limit.

The temperature rise in any part of a machine depends (1) on the amount of energy dissipated in the form of heat, (2) on the specific radiating constant of the material, (3) on the effective cooling surface, and (4) on the velocity of the air which passes by and around any particular part.

204. Cooling Surface.—Practice has shown that for *stationary armatures,* where the losses are composed of those in the iron and the armature copper, a cooling surface of about *1 to 1.5 square inches per watt loss* is a fair figure.

The following cooling surfaces are to be considered:

The inner cylindrical surface, equal to $l \times D \times 3.14$;
the external cylinder, equal to $l \times D_2 \times 3.14$;
the two side faces which are equal to $2 \times \frac{(D_2^2 - D^2) \times 3.14}{4}$;

and the surfaces inside the ventilating ducts, of similar expression as the two side faces.

205. Temperature Rise in Stationary Armatures.—For the calculation of temperature rise in the *stationary armature,* the following formula gives good results:

$$T_1 = 75\frac{W}{O_1} \quad\dots\dots\dots\dots\dots\dots (\mathbf{40})$$

where W = the total amount of the armature losses in watts;

O_1 = the value of the cooling surface in square inches, calculated as shown in Paragraph **204**; and

T_1 = the temperature rise in Fahrenheit degrees.

In most cases the application of ventilating ducts every 3 to 4 inches of iron length will be found sufficient, providing that the width of such a duct is not less than 0.5 inch, and that there is free access left for the air to pass through.

206. Temperature Rise in Rotating Magnet Wheels. The cooling conditions in a rotating magnet wheel are naturally very favorable, and for average peripheral speeds, a specific cooling surface of *0.75 to 1 square inch per watt loss* dissipated in heat, will be sufficient to keep the temperature rise within moderate limits.

The following formula provides a satisfactory method for checking the temperature rise:

$$T_2 = K \times \frac{W_m}{O_2\,(1+0.0002\,V)} \quad\dots\dots\dots\dots (\mathbf{41})$$

in which W_m = the energy loss in watts, which is equal to the excitation energy consumed in the magnet coils;

O_2 = the cooling surface composed of the external cylindrical surface of the coils, and the two sectional areas of the pole cores, all measured in square inches;

V = the peripheral speed in feet per minute;
K = *a constant* which varies somewhat with different types of construction.
T_2 = temperature rise in degrees Fahrenheit.

The factor K may be taken equal to 100 when the winding depth does not exceed 1.5 inches and for larger coils K should be about 120, assuming that the coils consist of insulated wire. For flat edge wound strip coils, this factor is as low as 85.

To provide good ventilation and cooling, it is further required that the coils should not be too close together on the periphery, and that the air gap should not be too small.

207. Determination of Air Gap.—In the determination of the clearance or air gap the amount of necessary field ampere turns in the first instance is decisive.

For a machine of a certain capacity at a certain speed, the most favorable amount of armature ampere turns is fixed in accordance with the data given in Par. **182**.

From the conditions of regulation, the ratio between the armature and field ampere turns is given, so that the number of the necessary field ampere turns can be calculated for the normal open circuit voltage. As a general rule about 75% of the same should be utilized in the air gap.

The exact predetermination of the air gap is not an all important condition, as it is easily altered in the workshop if required, but one would do well to take a somewhat smaller gap for a new type of alternator, so that if any alteration is required it simply means the enlarging of the same by turning material off the *pole shoes*.

208. Advantages of Large and Small Air Gaps.—The application of a small air gap results in the employment of a small number of field ampere turns and reduces the leakage of the magnet system.

In favor of large air gaps, it may be mentioned, that the effect of any magnetic dissymmetry is diminished and that the eddy current losses are considerably reduced, which is of importance where solid pole shoes are used.

209. Final Determinations.—In summarizing the contents of Pars. **181** to **208**, it may be mentioned, that for the basis of a successful design, the data of Fig. 62 should be used, from which the most favorable utilization of the iron and copper may be attained.

The choice of dimensions, the current and magnetic densities and the necessary mechanical details are then proceeded with in such a manner that the specified efficiencies and temperature rise are complied with.

With the object of illustrating the method of calculation and to show the adaptability of the empirical data already given, the design of actual machines is given hereafter, from which the design of various types of alternators should be a simple and well understood matter.

THREE PHASE, REVOLVING FIELD ALTERNATOR DESIGN.

210. General Specification for Three Phase Alternator.—A 400 KVA. revolving field type, three phase generator, capable of delivering a current of 66 amperes at a normal working E.M.F. of 3,500 volts, has the dimensions indicated in Fig. 66. The alternator, at a speed of 500 revolutions per minute, generates current at 50 cycles per second. The armature is star connected and the winding is placed in 72 slots, each slot containing 18 conductors, which consist of 2 parallel connected No. 9 S.W.G. wires. The armature coils are former wound and held in the slots by means of 0.2 inch thick fibre wedges. The coils are properly insulated from the iron by 0.08 inch thick micanite channels. The winding is of the long coil type, similar to that shown in Fig. 51.

The field system has 12 poles, each carrying a coil of 35 turns, which is built of edge wound flat copper strips, having a thickness of 0.125 inch and a width of 1.125 inches. The turns are insulated from each other by press-spahn 0.02 inch in thickness. The material of the armature core is soft annealed sheet iron of 0.02 inch and that of the magnet pole 0.04 inch thick, while the magnet wheel rim is of ordinary cast iron. The excitation current is supplied by a dynamo with an E.M.F. of 30 volts.

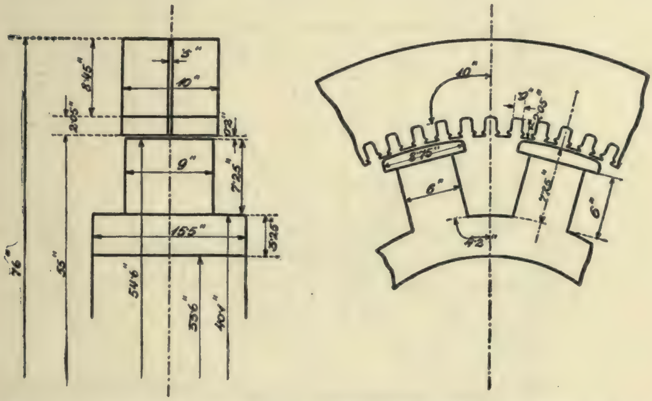

FIG. 66.—400 KVA., 3,500 VOLTS, 500 REVS., 50-CYCLE 3-PHASE ALTERNATOR.

The machine complies with the requirements of Par. **16**, regarding temperature rise, and for regulation and efficiencies see the actual test data given in Fig. 67.

211. Peripheral Velocity.—The alternator running at a speed somewhat above the standard, gives a peripheral speed of 7,150 feet per minute measured on the external diameter of the magnet wheel.

The periphery is equal to $54.6 \times 3.14 = 171.4$ inches, and according to Equation (**38**) the peripheral velocity is

$$\frac{171.4 \times 500}{12} = 7{,}150 \text{ feet per minute.}$$

Although the velocity is above the average value, there is no difficulty in designing the rotating part to have the necessary mechanical strength.

212. Pole System.—The poles are fixed to the wheel rim in dovetailed tunnels and the projecting part of the pole is of ample strength, having a thickness of 1.2 inches.

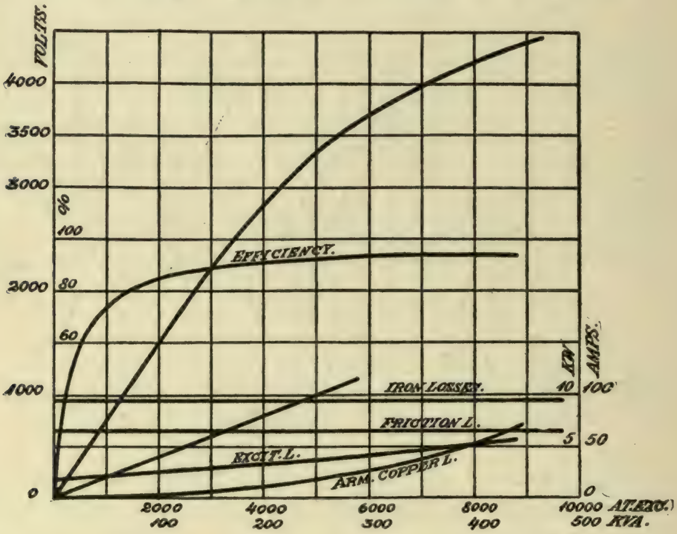

FIG. 67.—TEST DATA OF A 400 KVA., 3,500 VOLTS, 500 REVS., 50-CYCLE 3-PHASE ALTERNATOR.

The edge wound, flat copper strip magnet coils make a very reliable coil system.

The wheel rim section is large enough to be mechanically strong.

213. Pole Pitch.—The poles are 12 in number and according to Equation (**7**) the frequency $= \frac{500 \times p}{60} = 50$, where

$p = 6$; and the pole pitch is equal to:

$$\frac{171.44}{12} = 14.28 \text{ inches.}$$

214. Pole Arc Ratio.—The length of the pole arc is indicated in Fig. 66 as 8.75 inches; therefore the pole arc ratio is found to be:

$$\frac{8.75}{14.28} = 0.61,$$

which is a standard value.

The two edges of the pole shoes are well rounded off so that the magnetic lines will be less dense on this part than in the middle of the pole shoe, as such a condition favors the sinusoidal wave form.

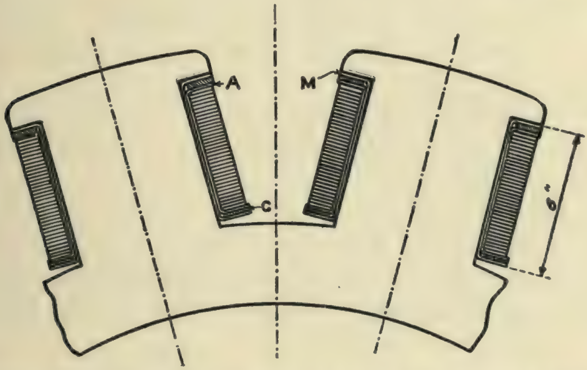

FIG. 68.—POLE WINDING, 400 KVA., 3,500 VOLTS 3-PHASE ALTERNATOR.

215. Winding Details.—The pitch on the external diameter of the wheel rim is equal to

$$\frac{40.1 \times 3.14}{12} = 10.46 \text{ inches}$$

where 40.1 inches is the diameter given in Fig. 66.

The width of the pole core being 6 inches, the smallest space available for the winding is equal to

$$\frac{10.46 - 6}{2} = 2.23 \text{ inches},$$

which is ample for the coil of 1.125 inches in depth together with an insulating spool, *A*, 0.06 inch thick and the protecting metal spool, *M*, 0.08 inch thick which is placed between the pole core and insulating spool, as indicated in Fig. 68.

In a radial direction, the magnet coil has a good tight fit, as the following calculation shows:

The total height of the pole is 7.25 inches. The thickness of the pole shoe being 1.2 inches there is left a free length of 6.05 inches, which is taken up by 35 0.125-inch copper strips, by 37 0.02-inch press-spahn sheets and by two metallic projecting pieces, *C*, as indicated in Fig. 68.

216. Size Factor.—It will be instructive to check the leading dimensions of the alternator, by applying the rule given in Par. **196**:

The normal output of the machine is 400 KVA. when running at a speed of 500 r.p.m.; the bore of the armature is equal to 55 inches, and the iron length with its paper insulation 9.5 inches; so that the size factor of the alternator will be:

$$f = \frac{55^2 \times 9.5 \times 500}{400} = 36 \times 10^3.$$

This, when compared with the average value given in Fig. 64, indicates that the design and leading dimensions have not been cut too fine.

This comparison serves simply as a guide and in no way decides if the design is economical, or not.

217. Distribution of Material.—In order to ascertain if the design will give the reasonable features of a commercial alternator, together with the most favorable distribution of the material, it is necessary, in the first instance, to investigate if the iron and copper sources are properly divided.

218. Normal Magnetic Flux.—According to Pars. **182** to **187**, a machine of a certain capacity per revolution should have a certain amount of normal magnetic flux, to make it a successful commercial design.

In the present case $\frac{KVA.}{N} = 0.8$, the normal output being 400 KVA. and the number of revolutions 500. From Fig. 62, the value of the total flux for the normal open circuit voltage should be about 55×10^6 magnetic lines; that is, the flux per pole should be about $F_2 = \frac{55 \times 10^6}{12} = 4.6 \times 10^6$ lines; while from Equation (**33**):

$$2{,}040 = \frac{2.3 \times 50 \times 24 \times 18 \times F_2}{10^8},$$

which gives

$$F^2 = 4.12 \times 10^6 \text{ lines per pole.}$$

In the above equation 2,040 is the phase E.M.F. in volts; 2.3 is the value of the form factor corresponding to the two slot winding and to the pole arc ratio of 0.61, see Table **14**; and 24 × 18 gives the number of the armature conductors per phase.

219. Actual Flux Value.—The actual flux value of 4.12×10^6 lines is about 10% smaller than that indicated by Fig. 62; consequently it is concluded that the number of armature conductors has been chosen somewhat higher than usual and that the value of the regulation can only be obtained by the application of more field ampere turns than is usually found in a standard design.

220. Choice of Lower Flux.—The choice of the somewhat lower flux permits the reduction of the iron, but on the other hand requires an increase of copper. As will be seen later from the present design, the amount of field copper has been kept normal with the consequence of a somewhat worse regulation than usual, on a non-inductive load.

221. Value of Armature Ampere Conductors.—The number of armature ampere conductors per inch periphery gives further data on which to criticise the design.

The normal current of the star connected armature is:

$$\frac{400,000}{1.73 \times 3,500} = 66 \text{ amperes per phase, see Equation } (\mathbf{5}).$$

The total number of armature conductors in all three phases equals 72 × 18 = 1,296, making the number of armature ampere conductors equal to 1,296 × 66 = 85,536.

222. Value of Peripheral Density.—From Par. **211** we take the value of the periphery as 171.4 inches so that the peripheral density is equal to $\frac{85,536}{171.4} = 500$ per one inch armature periphery, which, when compared with the data of Fig. 63, will be found a little high.

After summarizing the results, that the armature copper source has been chosen somewhat ample and that the peripheral speed is higher than the average value, it is concluded that the diameter is of a suitable size, as it permits the proper placing of the slightly increased armature copper and insures a good arrangement for cooling.

223. Ratio Between Slot Depth and Width.—The 85,536 armature ampere conductors are to be placed in the 72 slots, so that each slot will contain a value of 1,188 ampere conductors which, as practice has proved, will permit the application of a properly shaped slot with due regard to leakage and correct proportions of slot and tooth width.

The ratio between the slot depth and width is equal to

$$\frac{i}{s} = \frac{2.05}{0.9} = 2.28,$$

which is a good average value.

224. Arrangement of Wires in Slots.—The 36 No. 9 S.W.G. wires, each wire with an external insulated diameter of 0.16 inch, are most conveniently arranged inside the slots as indicated in Fig. 69.

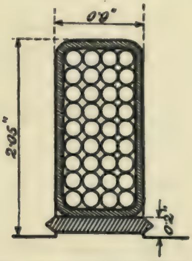

Fig. 69.—Slot Winding of the 400 KVA., 3,500 Volts 3-Phase Alternator.

225. Calculation of Slot Width.—The slot width is calculated as follows: The four wires in one row require a space of 4 × 0.16 = .64 inch; the 0.08 inch thick micanite tube takes up 0.16 inch. Further, it is necessary to allow about 0.04 inch as play and 0.04 inch for the irregularity of the assembled stampings, thus making a total width of 0.88 inch.

226. Calculation of Slot Depth.—The determination of the slot depth is carried out as follows: Nine times the diameter of the wire is equal to 9 × 0.16 = 1.44 inches, see Fig. 69; the micanite occupies 0.16 inch; for play it is necessary to add 0.10 inch, and the fixing wedge requires an additional 0.25 inch, thus giving a total depth of 1.95 inches. In the actual machine a standard slot of 0.9 inch by 2.05 inch has been employed.

227. Value of Space Factor.—The available winding space is properly utilized, that is, there is no superfluous insulation material used, as concluded from the value of the space factor, 0.32, where the air section of the slot is $0.9 \times 2.05 = 1.84$ square inches and the copper section 0.586 square inch, which in their ratio $\frac{0.586}{1.84} = 0.32$.

228. Calculated Copper Loss.—Regarding the specific utilization of the armature copper, it is found, that for 66 amperes normal current, a section of $2 \times 0.01629 = 0.0326$ is provided in which the current density will be $\frac{66}{0.0326} = 2{,}030$ amperes per square inch. This is a good average value, corresponding to a loss of 10 watts per pound of copper, see Fig. 31.

229. Section and Form of Coils.—The necessary section of conductor in the present design, is obtained by using two No. 9 S.W.G. wires in parallel, as one wire of a large gauge will not permit the same favorable slot shape and, what is still more important, the winding of such a thick wire is a difficult job and would tend to increase the labor costs of the armature.

The slots being open, former wound coils of double cotton covered, high conductivity, round copper wire are used.

230. Average Length of Mean Turn.—For a voltage of 3,500 between phases and 2,040 volts per phase, it is necessary to allow an air distance of about 1.75 inches between the coils of any two phases and as much between the projecting part of the coil and the nearest part of the iron body. Under these conditions the average length of mean turn in the armature coils is equal to 77 inches.

231. Section of Teeth.—In order to check the dimensions of the iron parts it is necessary to calculate the densities in the same, and the magnetic induction in the teeth will be especially decisive regarding the length of the armature. Par. **218**, gives a normal armature flux of 4.12×10^6 lines per pole; the section offered to this flux by the teeth is equal to $\frac{a}{o} \times l \times r \times 0.9 = \frac{8.75}{2.4} \times 9.5 \times 1.5 \times 0.9 = 47$ square inches, with reference to Fig. 66.

232. Calculation of Teeth Section.—In machines with small or medium sized bore, it will be advisable to calculate the tooth section at the bottom and at the top part of the toothed body. In this particular case o on the inside periphery $= \frac{172.4}{72} = 2.4$ inches; and $r = o - s =$ 1.5 inches.

At the top of the teeth, $o = \frac{59.1 \times 3.14}{72} = 2.57$ inches,

$$\text{and } r = o - s = 2.57 - 0.9 = 1.67;$$

so that the average value of tooth section, with $r = \frac{1.5 + 1.67}{2} = 1.58$, is $\frac{8.75}{2.4} \times 9.5 \times 1.58 \times 0.9 = 49$ square inches with an average magnetic density of

$$\frac{4.12 \times 10^6}{49} = 84{,}000 \text{ lines per square inch.}$$

233. Value of Iron Loss.—This value is about 20 per cent. higher than the usual mean density corresponding to 50 cycles, but it may be considered a good value, as it does not cause more hysteresis and eddy current losses than $5.5 + 1.25 = 6.75$ watts per pound of iron.

The calculation of the losses in this particular case will show that a standard efficiency is easily obtained.

234. Length of Armature.—The effective iron length of the armature = 8.6 inches; to this has to be added about 10 per cent. on account of the paper insulation between the laminations and ½ inch for a ventilating duct, making the overall armature length equal to 10 inches.

235. Height of Core Above Slots.—The height of the armature core above the slots in the present machine, is equal to 8.45 inches and the section $8.45 \times 9.5 \times 0.9 = 72$ square inches.

The magnetic density is somewhat lower than the average value indicated in Fig. 26, calculating out at $\frac{4.12 \times 10^6}{2 \times 72}$ = 28,600 lines per square inch.

The low value of the density and the increased height of the armature core above the slots, is due to the fact that the same stamping, which is a standard size, is used for generators with a smaller number of poles and a larger flux per pole.

236. Calculated Iron Loss.—The loss per lb. of iron is 1.075 watts, taking both the hysteresis as well as the eddy currents into account.

237. Calculation of Open Circuit Characteristic.—The calculation of the open circuit characteristic is the next step. After having decided that the dimensions of the armature are not subject to any radical criticism, the calculated no-load curve should then be compared with the test results, to enable the calculation of the field turns and the determination of the short circuit characteristic to be carried out. The different load conditions, with the corresponding regulation, may then be discussed later with the different losses and efficiencies.

238. Calculated Leakage Factor.—The determination of the flux in the field system is made in the first instance and therefore the leakage factor has to be fixed.

From Equation (**26**) this factor may be calculated fairly exact:

$$\sigma = 1 + \frac{r_0}{r_1^1};$$

where
$$r_0 = \frac{0.313}{\frac{a \times r \times l}{o \times \delta} + \frac{a \times l \times \left(u + \frac{s}{2}\right)}{o(u + \delta)}};$$

and
$$r_1^1 = \frac{0.313}{\frac{4c \times f}{n} + \frac{4d \times f}{m} + \frac{4b \times d}{m + b}};$$

with

$$r_0 = \frac{0.313}{\frac{8.75 \times 1.5 \times 9.5}{2.4 \times 0.2} + \frac{8.75 \times 9.5 \times (0.28 + 0.45)}{2.4 \times (0.28 + 0.2)}} = \frac{0.313}{260 + 54} = \frac{10}{10^4};$$

$$r_1^1 = \frac{0.313}{\frac{4 \times 1.25 \times 9}{5.53} + \frac{4 \times 7.25 \times 9}{5.6} + \frac{4 \times 6 \times 7.25}{11.6}} = \frac{0.313}{8 + 46 + 15} = \frac{46}{10^4};$$

then
$$\sigma = 1 + \frac{10}{46} = 1.22.$$

The value $\sigma = 1.25$ is very close to the actual factor.

In order to determine four points of the open circuit characteristic, proceed as in Example **23**, Par. **178**.

239. Calculation of Field Flux.—By means of Equation (**33**) it has been found that for the generation of 3,500 volts between any two phases, a useful flux of 4.12×10^6 lines is required, the corresponding field flux being $F_1 = \sigma \times F_2 = 1.25 \times 4.12 \times 10^6 = 5.15 \times 10^6$ lines. The useful flux varies proportionally with the voltage; that is, for 4,200 volts, $F_2 = 4.95 \times 10^6$; or, for 3,000 volts, $F_2 = 3.54 \times 10^6$, etc.

Assuming that the leakage factor is the same for various degrees of saturation, the corresponding field fluxes are: For 4,200 volts, 6.18×10^6, and for 3,000 volts, 4.42×10^6 etc.

240. Various Iron Sections.—The various iron sections of the armature have been already determined in Par. **231** to **235**, and the air path reluctance is given in Par. **238**.

The sectional area of the pole core is equal to $f \times b \times .96 = 9 \times 6 \times .96 = 52$ square inches; and that of the wheel rim, $g \times h = 15.5 \times 3.25 = 50$ square inches.

241. Respective Path Lengths.—The various lengths of the paths are taken from Fig. 66 and systematically collected in Table **18**, together with the various sectional areas and magnetic densities.

By means of Fig. 46, the value of the ampere turns per unit length of the differently saturated parts may be fixed, and by multiplying them with the respective path lengths, the value of the necessary ampere turns for the iron paths is obtained.

The amount of ampere turns utilized for the air path is equal to the reluctance multiplied by the useful flux.

242. The Resultant Open Circuit Characteristic.—The open circuit characteristic resulting from the calculation, will be found in close accordance with that obtained by tests on the actual machine.

It should be noted that the greatest contribution to the iron path is located in the field system and that the normal open circuit voltage is just on the knee or bend of the curve, where the ampere turns belonging to the iron path are about 25 per cent. of the total value, as

$$\frac{1.460}{5,580} = .25.$$

243. Calculation of the Factor k_s.—The determination of the short circuit characteristic is very simple. In the first instance it is necessary to calculate the factor k_s of Equation (**15**).

According to Equation (**29**) this factor can be expressed

TABLE 18.

E. M. F.				4,200		3,500		3,000		2,000	
Armature Flux.				4.95×10^6		4.12×10^6		3.54×10^6		$2\ 36 \times 10^6$	
Field Flux.				$6\ 18 \times 10^6$		$5..6 \times 10^6$		4.42×10^6		2.95×10^6	
Material and Sectional Area in Sq. Inches of:	Wheel Rim.	Cast Iron. 50	Magnetic Densities and Corresponding Ampere Turns per One Inch Length.	61,800	320	51,600	190	44,200	130	29,500	60
	Pole Core.	0.04″ Sheet. 52		119,000	330	99,000	88	85,000	42	57,000	16
	Teeth.	0.02″ Sheet. 49		101,000	95	84,000	40	72,000	27	48,000	12
	Armature Core.	0.02″ Sheet. 72		34,400	6	28,600	5	24,500	4	16,400	3
Length of Magnetic Paths in Inches.	Wheel Rim.	4.2	Ampere Turns of the Paths.	1,340		800		545		250	
	Pole Core.	6		1,980		530		250		95	
	Teeth.	2.05		195		80		55		25	
	Armature Core.	10		60		50		40		30	
r_0		$\frac{10}{10^4}$		4,950		4,120		3,540		2,360	
Total Ampere Turns per Pole.				8,525		5,580		4,430		2,760	

by $k_s = 1 + \frac{r_0}{r_2^1}$ where r_2^1, in the present case, gives a value of

$$r_2^1 = \frac{0.313}{\frac{4\times 2.05\times 9.5\times 2.4}{0.9\times 14.4} + \frac{4\times 2.05\times 1.5(14.4+2.40)}{14.4\times 2.4} + 28.5}$$

$$= \frac{0.313}{4.5+6+28.5} = \frac{64}{10^4}$$

for the reluctance of the field leakage path.

The air gap reluctance has been found in Par. **238** to be $r_0 = \frac{10}{10^4}$ so that the factor $k_s = 1 + \frac{10}{64} = 1.16$, which means, that if the *effective* armature back ampere turns on short circuit are equal to say 1,000, the corresponding field ampere turns will be $k_s \times 1{,}000 = 1{,}160$.

244. The Short Circuit Characteristic.—Suppose for example, the field excitation A_1 is equal to 2,000 ampere turns, the resulting short circuit current will have a value of

$$2p\times A_1 = k_s\times 2.12\times \frac{Z\times C}{2} = 12\times 2{,}000 = 1.16\times 2.12\times \frac{72\times 18}{3\times 2}\times C,$$

where $\frac{Z}{2}$ is the number of armature turns per phase and C the short circuit current per phase, which in this particular case is equal to 45.5 amperes.

This current value erected as ordinate above the excitation as abscissa, is one point, B, on the characteristic curve, which is a straight line, another point O being the zero point of the co-ordinate system.

It is interesting to note, that the short circuit current corresponding to the excitation of the normal open circuit voltage is about 1.9 times larger than the normal armature current, which is 66 amperes.

From the above results it will be seen that the calculated and actual test results are very similar.

245. Determination of Voltage Drop.—The voltage drop and the necessary excitation should be calculated for an external load having a power factor of 0.8, as the alternator is intended to work on a power circuit. In accordance with the method developed in Pars. **130** to **134**, the curve of the square of the apparent magnetic

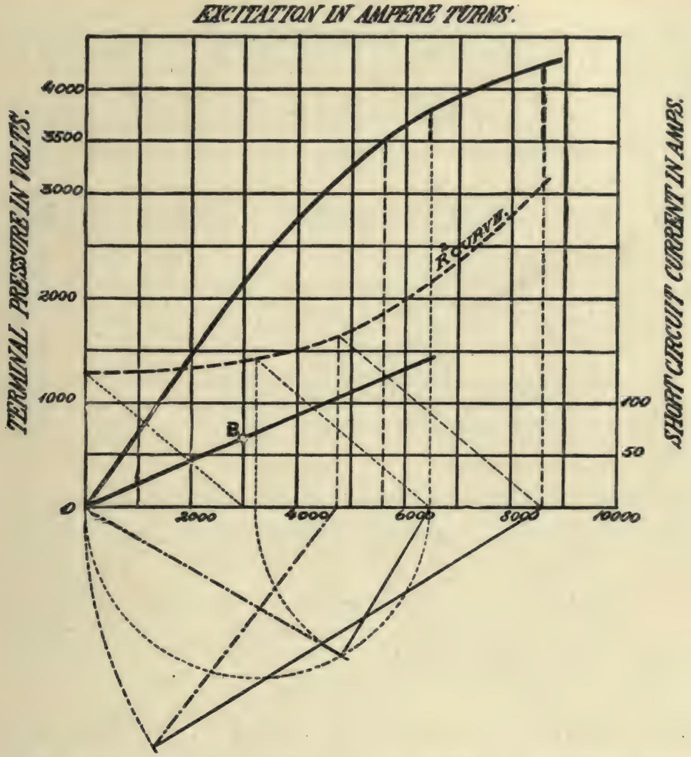

Fig. 70.—Characteristics of a 400 KVA., 3,500 Volts, 50-Cycle 3-Phase Alternator.

resistance is to be determined and the graphical solution carried out as in Fig. 70.

246. Actual Drop.—For $\cos\varphi = 0.8$ inductive full load, a voltage drop of $\frac{700}{3,500} = 20$ per cent. is obtained; and for a non-inductive full load the voltage drop is equal to $\frac{300}{3,500} = 8.6$ per cent., which is somewhat larger than the average value and has been already predicted in the preliminary criticism of the design.

247. Calculated Excitation Current.—From Fig. 70 it follows that if the armature carries a $\cos\varphi = 0.8$ lagging current of 66 amperes, the excitation ampere turns must be equal to 8,550, in order to maintain the normal terminal E.M.F. of 3,500 volts.

The number of pole turns being 35, the maximum excitation current required is equal to $\frac{8,550}{35} = 244.5$ amperes.

248. Excitation at Half Load.—In order to calculate the excitation losses on inductive half load, the regulation is determined for an armature current of 33 amperes. The graphical method gives in this case a field excitation of 7,000 ampere turns, or an equivalent current of 200 amperes.

249. Current Density of Field Winding.—The specific utilization of the field copper is very satisfactory, as the current density for the maximum excitation is equal to $\frac{244.5}{.125 \times 1.125} = 1,740$ amperes per square inch area, which corresponds to a loss of 7.5 watts per one pound of copper, see Fig. 31. The use of edge wound, bare, flat copper strips, would permit a slightly higher current density, especially with such a high peripheral speed as specified for this machine; but as the resulting efficiency is improved, due to the smaller density employed, namely, 1,740 amperes per square inch, there is no need for any alteration.

250. Length of Field Winding.—The length of mean field turn is equal to 36 inches; therefore the total length of the 12 field coils which are connected in series is $12 \times 35 \times 36 = 15{,}120$ inches.

251. Weight of Field Copper.—The sectional area of a turn being equal to $.125 \times 1.125 = 0.1405$ of a square inch and the specific weight of the copper assumed as 0.32 lb. per cubic inch, the weight of the field copper will amount to $15{,}120 \times 0.1405 \times 0.32 = 680$ pounds.

252. Resistance of Field Winding.—If the hot copper winding has a specific resistance of $\frac{8}{10^7}$ ohms for a length of one inch with a section of one square inch, the resistance of the 12 field coils in series will be equal to $\frac{15{,}120}{0.1405} \times \frac{8}{10^7} = 0.0865$ ohm.

253. Voltage of Exciting Current.—From Par. **247**, the maximum excitation current required is 244.5 amperes, which implies a maximum voltage on the field terminals of $244.5 \times 0.0865 = 21.5$ volts.

The exciter should be capable of supplying a higher voltage than above mentioned, because there are additional losses in the connecting cables and between the slip rings and brushes. A certain margin should be allowed for the regulating resistance.

An exciter with a terminal pressure of 28 volts will be found ample to supply the field system of this alternator.

254. Temperature Rise of Field Coils.—The maximum energy utilized in the field coils will be $244.5^2 \times 0.0865 = 5{,}150$ watts which will cause a temperature rise of about 42°F., according to the following calculation based on the data in Par. **205**.

The cooling surface of a coil is composed of the external cylindrical surface which is about

$$6 \times (11.6 + 8.6) \times 2 = 242 \text{ square inches.}$$

The two iron sections, one next to the pole shoe, and the other next to the wheel rim, are equal to $2 \times 6 \times 9 = 108$ square inches. Therefore, the total cooling surface of all 12 coils is equal to $12\ (242 + 108) = 4{,}200$ square inches.

According to Equation (**41**) the temperature rise is equal to

$$85 \times \frac{5{,}150}{4{,}200(1 + 0.0002 \times 7{,}150)} = 42^\circ \text{ F.}$$

During the actual tests of this machine a temperature rise of 46°F. was recorded.

255. Length of Armature Winding.—The maximum energy utilized in the armature winding is found as follows:

The length of mean turn equals 77 inches from actual measurement; or, if calculated by means of Equation (**12**),

$$L = 2(10 + 2 \times 14.4) = 77.6 \text{ inches.}$$

The number of turns per phase being $12 \times 18 = 216$, the length of the turns which are connected in series will be $77 \times 216 = 16{,}632$ inches, or, that of all three phases is equal to 49,896 inches.

256. Weight of Armature Copper.—Each conductor consists of two parallel connected No. 9 S.W.G. wires, the effective section of which is equal to $2 \times 0.01629 = .03258$ square inches; therefore the weight of armature copper is equal to $49{,}900 \times 0.03258 \times 0.32 = 520$ pounds.

257. Loss in Armature Winding.—The maximum current density is 2,030 amperes per square inch, so that the maximum loss, in accordance with the data of Fig. 31, will equal $520 \times 10 = 5{,}200$ watts.

258. Weight of Teeth.—The effective volume of a tooth is expressed by $0.9 \times r \times l \times i = 1.58 \times 9.5 \times 2.05 \times 0.9 =$ 28.0 cubic inches; so that the weight of all the teeth will be $72 \times 28 \times 0.28 = 570$ lbs. where the specific weight of the iron is taken as 0.28 lb. per cubic inch.

259. Loss in Teeth.—According to Par. **232**, the mean tooth density is 84,000 lines per square inch, resulting in a hysteresis loss of 11 watts at a frequency of 100 and an eddy current loss of 5 watts per lb. of iron at a similar frequency.

In the present case, the frequency being 50, the specific losses are, hysteresis $5.5 = \frac{11}{2}$ watts and eddy current $\frac{5}{4} = 1.25$ watts per lb., thus making in all, a total loss in the teeth of $570\ (5 + 1.25) = 3{,}550$ watts.

260. Weight of Core.—The weight of the armature core above the slots equals

$$\frac{(76^2 - 59.1^2) \times 3.14}{4} \times 9.5 \times 0.9 \times 0.28 = 4{,}300 \text{ lbs.},$$

where 76 inches is the external diameter, 59.1 inches the internal diameter of the core, and 9.5 inches is the armature length which includes the insulation between the laminations.

261. Total Loss in Core.—In Paragraph **235**, the corresponding magnetic density is given as 28,600 lines, which implies a loss of 1.9 watts per lb. as hysteresis loss, and 0.9 watt per lb. as eddy current loss, both figures calculated on the basis of a frequency of 100.

For this machine the hysteresis loss equals 0.95 watt per lb. and eddy current loss, 0.225 watt per lb.

The total core loss will therefore be equal to

$$4{,}300(0.95 + 0.225) = 5{,}050 \text{ watts.}$$

262. Total Loss in Armature.—The total amount of energy dissipated in the form of heat in the armature is equal to

$$5{,}200 + 3{,}550 + 5{,}050 = 13{,}800 \text{ watts.}$$

263. Cooling Surface and Temperature Rise.—With reference to Par. **204**, the available cooling surface in the present design is as follows:

The external cylinder surface: $76 \times 3.14 \times 9.5 = 2{,}300$ square inches;

the inner cylinder surface: $55 \times 3.14 \times 9.5 = 1{,}650$ square inches;

the two outer side faces: $2 \times \frac{76^2 - 55^2}{4} \times 3.14 = 4{,}300$ square inches;

and the two faces inside the ventilating duct $= 4{,}300$ square inches;

making a total cooling surface of 12,550 square inches.

This gives 0.9 square inch per watt loss, and according to Equation (**40**), the temperature rise will be:

$$75 \times \frac{13.800}{12{,}550} = 82° \text{ F.}$$

The temperature rise is slightly high, and from all appearances, it would have been advisable to employ a second ventilating duct.

264. Total Losses in Alternator.—The various losses in the alternator under discussion are as follows:

The friction and ventilation losses are on the basis of the data in Fig. 25 estimated at................7,000 watts;

the iron losses have been calculated as.......8,600 watts;

the armature copper losses for a phase current of 66 amperes equal..............5,200 watts;

and for half load current, namely, 33 amperes . . . . .1,300 watts;
the excitation energy of the field coils, when the armature carries a cos $\varphi = .8$ lagging current of 66 amperes, equals. . . . . .5,150 watts;
and for a cos $\varphi = .8$ lagging current of 33 amperes . . . . .3,450 watts;
The *total losses* for cos $\varphi = .8$ inductive full load are equal to $7,000 + 8,600 + 5,200 + 5,150 = 25,950$ watts.

265. Efficiency.—The efficiency at full load, with cos $\varphi = .8$, will be

$$\frac{400,000}{425,950} = 94\%.$$

On half load, the total energy loss is 20,350 watts; consequently the half load efficiency is equal to

$$\frac{200,000}{220,350} = 91\%.$$

The efficiency at full load, and in particular at half load, is slightly better than the usual efficiency of a standard machine, see Table **1**. The reason for this is, that in this particular alternator, the weight of armature copper is somewhat more than usual and this *variable* loss item improves the half load efficiency.

266. Total Weight of Copper.—The weights of material used in this particular machine are as follows:

Armature copper	520 lbs.
Field copper	680 "
Total copper used	1,200 "

which is less than that of a standard speed 400 KVA. alternator.

This difference is due to the comparatively small number of field ampere turns, which produces a higher voltage drop than the average value.

267. Total Weight of Iron.—The total weight of the armature stampings is equal to..................4,870 lbs.; a value below that indicated in Fig. 14.

The weight of the pole stampings amounts to

$$12 \times (6 \times 9 \times 6 + 1.25 \times 9 \times 8.75) \times 0.28 = 1{,}450 \text{ lbs.};$$

and that of the cast iron wheel rim to

$$\frac{40.1^2 - 33.1^2}{4} \times 3.14 \times 15.5 \times 0.28 = 1{,}750 \text{ lbs.}$$

Total amount of iron, 8,070 lbs.

268. Summary of Results Obtained.—It should be of interest to know that the results of the actual tests on the machine under discussion agree with the calculated results. As close regulation was not specified, so more armature turns and less field ampere turns have been employed than is usual in a standard design.

The copper is used economically, but it was impossible to dimension the armature iron in the most advantageous way, as the free choice of the designer was affected by the condition that he had to employ existing armature stampings with a somewhat excessive height above the slots. The tendency was to save material and a slightly smaller iron length has been applied, so that the tooth density with the same iron losses became slightly higher.

In order to approach a standard design, the alternator should have less armature ampere turns, but more field ampere turns, which could have been effected by a slight increase of the air gap. Further, the armature would be longer and the core height smaller.

DESIGN OF A LOW SPEED, REVOLVING FIELD TYPE, TWO PHASE ALTERNATOR.

269. General Specification of Alternator.—The dimensions of the flywheel type generator under discussion are given in Figs. 59 and 60. The normal output of this two phase alternator with two independent armature phases is 375 KVA., when running at a speed of 93¾ per minute and generating a phase current of 62½ amperes at 50 cycles, with a terminal voltage of 3,000 volts.

The armature is two phase wound and the winding is placed in 256 slots, each slot containing 15 conductors, and each conductor composed of two parallel connected No. 9 S.W.G. wires. The coils are placed inside the open slots which are insulated by a $\frac{3}{32}$ inch micanite tube. The type of winding employed is the one given in Fig. 48.

The magnet system consists of 64 machine wound coils, the size of conductor being No. 1 S.W.G. double cotton covered round wire. The number of turns per coil is 80.

The material of the armature core is 0.02 inch soft annealed sheet iron, that of the pole pieces 0.04 inch stampings, and the wheel rim is made of ordinary cast iron.

The generator is driven by a direct coupled steam engine and has to work in parallel with other machines of similar design, while supplying current to a power circuit of $\cos\ \varphi = 0.8$.

270. Determination of Wheel Diameter.—The wheel diameter has been determined with particular regard to the provision of the necessary space for the magnet winding and the application of the flywheel effect in the magnet wheel itself.

271. Flywheel Effect.—The engine makers specified in this particular case a flywheel effect which is equal to $W \times D^2 = 2{,}200$ tons feet square, where W equals weight of revolving part in tons, and D the diameter in feet.

This condition is in the present case complied with, as the total weight of the magnet pieces and coils is 3.25 tons, and their gyration diameter is 13.5 feet; consequently the flywheel effect of this part is equal to $3.25 \times 13.5^2 = 590$ tons feet square.

The weight of the cast iron rim together with the arms is about 12.5 tons, and the diameter 11.75 feet, so that the flywheel effect in this particular part is equal to $12.5 \times 11.75^2 = 1{,}730$ tons feet square; from which a total effect of 2,320 tons feet square is obtained.

272. Peripheral Speed.—The peripheral speed at the external diameter of the magnet wheel is

$$\frac{169 \times 3.14 \times 93.75}{12} = 4{,}150 \text{ feet per minute,}$$

which is much lower than that of a standard speed alternator of the same capacity.

In the present case, an increase of the diameter would be disadvantageous from an electrical point of view, as well as with regard to the economy of material and to the mechanical construction and strength of the machine.

273. Winding Space.—The following calculation indicates that there is ample room for the necessary field winding.

The periphery on the bottom of the coils is equal to $153 \times 3.14 = 480.4$ inches; so the available space for one coil side is $\frac{480.4}{2 \times 64} - \frac{3.95}{2} = 1.78$ inches, and the total coil depth is 1.5 inches.

274. Number of Poles.—The *number* of *poles* is equal to

$$\frac{93.75 \times p}{60} = 50 \text{ where } 2p = 64.$$

The value of the *pole pitch* is

$$\frac{D \times \pi}{64} = \frac{169 \times 3.14}{64} = 8.29 \text{ inches.}$$

Fig. 60 gives a pole arc of $\frac{4.5 + 5.6}{2} = 5.05$ inches, so that the *pole arc ratio* will be $\frac{5.05}{8.29} = 0.61$.

The edges of the pole pieces are cut in order that, as far as possible, a sinusoidal wave form may be obtained, see Fig. 71.

275. Output Coefficient.—The output coefficient of this low speed polyphase alternator is $\frac{169^2 \times 5.5 \times 93.75}{375} = 40.4 \times 10^3$, which agrees with that of a standard machine, see Fig. 64; but in spite of this fact the amount of material in the low speed machine will be found much in excess of that in a standard machine.

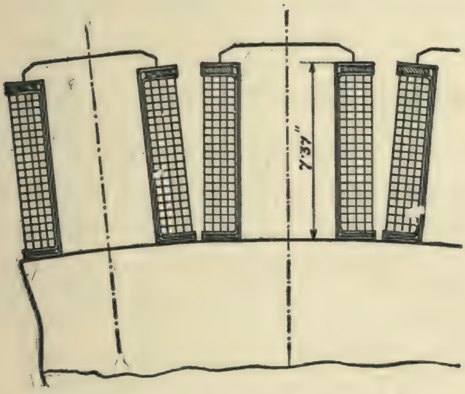

FIG. 71.—POLE WINDING, 375 KVA., 3,000 VOLTS 2-PHASE ALTERNATOR.

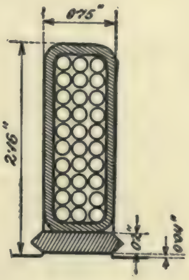

FIG. 72.—SLOT WINDING OF THE 375 KVA., 3,000 VOLTS 2-PHASE ALTERNATOR.

The difference is especially noticeable in the amount of idle material, such as the extra weight of material in the cast iron frame.

276. Normal Total Flux.—With regard to the basis of the most economical division of the active iron and copper material, we find that the normal flux is about 27 per cent. less than indicated in Fig. 62, as the ratio $\frac{KVA}{N} = \frac{375}{93.75} = 4$, requires $115 \times 10^6 = 2p \times F_2$ flux, while the actual flux, Fig. 62, is $64 \times 1.34 \times 10^6 = 86 \times 10^6$, see Par. **178**.

277. Useful Flux Per Pole.—In Par. **178**, the calculation of the no-load characteristic of this machine is given, and with a form factor of 2.34 the normal useful flux per pole is equal to 1.34×10^6, which corresponds to 3,000 volts open circuit voltage.

278. Peripheral Density.—The full load current per phase of the armature works out to be $\frac{375,000}{2 \times 3,000} = 62.5$ amperes and the number of armature conductors $256 \times 15 = 3,840$.

From this, the value of the armature ampere conductors is $3,840 \times 62.5 = 240,000$, which results in a peripheral density of $\frac{240.000}{169.4 \times 3.14} = 454$. This value is equal to that indicated in Fig. 63.

279. Particulars of Slots.—The armature winding is placed in 256 slots and the coils are arranged as shown in Fig. 48. The slot dimensions in Fig. 60 give a ratio of about 2.9 between the slot depth and width. As this value is very close to the specified limit, a fairly high armature leakage will be found.

The number of ampere conductors per slot in the present case, is equal to $\frac{240,000}{256} = 937$.

280. Space Factor of Slots.—Each conductor consists of two parallel connected No. 9 S.W.G. wires, so that each slot has 30 wires which are embedded in the slot, as indicated in Fig. 72.

The thickness of the micanite insulation is $\frac{3}{32}$ inches and from these particulars the space factor may be found.

The copper section in one slot is $30 \times 0.1629 = 0.4887$ square inches; the total area of a slot section is $2.16 \times 0.75 = 1.62$ square inches; and the ratio $\frac{0.49}{1.62} = 0.3$ is the space factor.

It should be noted that this factor is in accordance with the average data given in Fig. 9.

281. Current Density in Armature Winding.—The current density of the armature winding in this particular case points to the successful utilization of the copper section.

The normal current being 62.5 amperes and the sectional area of the conductor $2 \times 0.01629 = 0.03258$ square inches, it follows that the current density will be $\frac{62.5}{0.03258} = 1{,}940$ amperes per square inch.

282. Length of Armature Winding.—The length of mean armature turn has been found from actual measurements on the machine in question to be 44.4 inches, which, when expressed by Equation (**12**), would read $2(6 \times 1.95 \times 8.29) = 2 \times 22.2 = 44.4$ inches, so that the projecting length of idle copper length per turn is $1.95 \times 8.29 = 16.2$ inches.

The product of length of mean turn and the number of turns per phase will be $44.4 \times 64 \times 15 = 42{,}500$ inches, the total length of the series connected turns per phase.

283. Resistance and Weight of Armature Winding.—The hot resistance of each phase winding from Equation (**11**), is equal to $\frac{42.500}{0.03258} \times \frac{8}{10^7} = 1.04$ ohms;

therefore the energy loss in the armature winding amounts to $2 \times 62.5^2 \times 1.04 = 8{,}200$ watts, at the normal load of 62.5 amperes per phase.

The total weight of armature copper is equal to

$$2 \times 42{,}500 \times 0.03258 \times 0.32 = 885 \text{ lbs.}$$

284. Teeth Density.—With regard to the specific utilization of the iron material, we find in Par. **178**, a magnetic density in the teeth of 77,000 lines per square inch, which is a good average value, see Fig. 27.

The density in the armature core above the slots has been calculated as 22,400 lines and is a comparatively low value.

285. Weight of Armature Iron.—The total weight of the armature iron is composed of,

the weight of the teeth,

$$256 \times 5.5 \times 1.33 \times 2.16 \times 0.9 \times 0.28 = 1{,}020 \text{ lbs.,}$$

and the weight of the armature core,

$$\frac{186^2 - 173.7^2}{4} 3.14 \times 5.5 \times 0.9 \times 0.28 = 4{,}840 \text{ lbs.;}$$

from which we obtain a total of 5,860 lbs.

This value does not compare favorably with the data in Fig. 14, though the output factor is found equal to that of a standard machine.

286. Losses in Armature Iron.—The iron losses in the different parts of the armature are as follows:

The hysteresis loss per lb. of material in the teeth with a magnetic saturation of 77,000 lines, will, in accordance with Fig. 29, be equal to $9.6 \times \frac{50}{100} = 4.8$ watts, for a periodicity of 50.

Under the same conditions, the eddy current losses are 1.05 watts per lb. of material, so that the losses in the teeth amount to $1{,}020 \times 5.85 = 5{,}960$ watts.

The armature core, with its low degree of saturation, has the specific losses of 0.65 watts per pound in the form of hysteresis and 0.12 watts loss due to the eddy currents;

consequently the total core loss will be

$$4{,}840 \times 0.77 = 3{,}740 \text{ watts.}$$

It will be noticed, that in the present design the iron losses in the teeth are far in excess of those in the core, which is to be considered an unfavorable method of dissipating the energy loss in the form of heat. The amount of the total iron losses is very close to the utmost limit of the usual values.

287. Temperature Rise.—With regard to the temperature rise of the armature body, we find for the total energy waste of

$$8{,}200 + 5{,}960 + 3{,}740 = 17{,}900 \text{ watts,}$$

a cooling surface composed of an

internal cylinder of $169 \times 3.14 \times 6 = 3{,}150$ sq. in.; an
external cylinder of $186 \times 3.14 \times 6 = 3{,}500$ " " ;
two side faces of $2 \times \frac{186^2 - 169.4^2}{4} \times 314 = 9{,}200$ " " ; and
two faces inside the air duct of 9,200 " "

offering a total cooling surface of 25,050 sq. inches.

From Equation (**40**) a temperature rise of

$$T_1 = 75 \times \frac{17{,}900}{25{,}050} = 54^\circ\text{F. is obtained,}$$

which, compared with the actual measurement, is found somewhat low, especially around the teeth and winding, where the greater part of the losses appear.

288. Flux in Field System.—For the determination of the flux in the field system and calculation of the open circuit and short circuit characteristics, refer to Pars. **178** and **179**, in which are found the value for the leakage factor $\sigma = 1.52$ and for the constant $k_s = 1.33$. Such high values are to be anticipated in the case of alternators with a great number of poles and small iron length.

The normal density in the pole core has been found equal to 100,000 lines, which is a favorable degree of saturation to obtain a satisfactory knee or bend in the open characteristic curve.

The wheel rim contributes very few ampere turns to the required amount, as the sectional area has been fixed exclusively to obtain the specified flywheel effect.

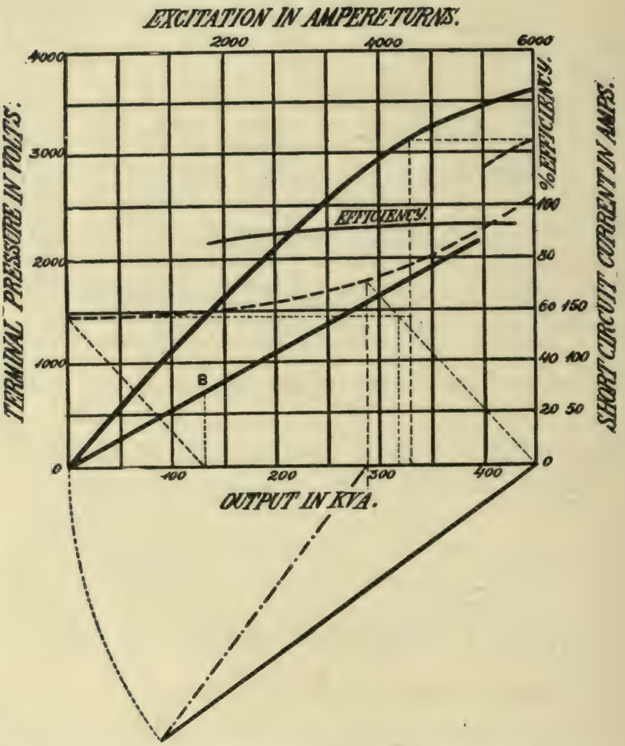

FIG. 73.—CHARACTERISTICS OF THE 375 KVA., 93¾ REVS., 50-CYCLE 2-PHASE ALTERNATOR.

289. Field Ampere Turns.—The maximum number of field ampere turns can be fixed, by determining the regulation of the alternator for $\cos \varphi = 0.8$ inductive full load, as the generator has to supply current to a power circuit.

In Fig. 73 the test data of this generator is given, which indicates a $\cos \varphi = 0.8$ inductive drop of 550 volts and a maximum excitation of 5,660 ampere turns per pole.

290. Current Density in Field Winding.—The number of turns per pole being 80, the maximum excitation current will be $\frac{5,660}{80} = 70.75$ amperes.

The field winding consists of No. 1 S.W.G. wire, which has a sectional area of 0.07069 square inch, so that the maximum current density in the wire will be $\frac{70.75}{0.07069}$ $= 1,000$ amperes per square inch. This value is a very liberal one, as seen from the calculation of the temperature rise in the field coils, see Par. **293**.

291. Length of Field Winding.—The length of mean field turn measured from the drawing, Fig. 71, is 28 inches; therefore the total length of the winding of the 64 coils is equal to $64 \times 80 \times 28 = 143,360$ inches, which represents a hot resistance of $\frac{143,360}{0.07069} \times \frac{8}{10^7} = 1.62$ ohms.

292. Excitation Voltage.—For the maximum excitation of 71 amperes, the terminal pressure on the field winding must be $71 \times 1.62 = 115$ volts; or, taking into account the various losses in the brushes and connecting cables, an exciter voltage of 125 volts will be found sufficient.

293. Temperature Rise in Field Winding.—The total weight of field copper is equal to

$$143,360 \times 0.07069 \times 0.32 = 3,250 \text{ lbs.},$$

and the maximum energy required for same is

$$71^2 \times 1.62 = 8,200 \text{ watts},$$

for which there is a radiating surface composed of the external cylindrical surface of

$$64 \times 7.37 \times 31 = 14,500 \text{ square inches},$$

and the two iron sections, one adjoining the pole shoe and the other the wheel rim, of

$$64 \times 2 \times 5.4 \times 3.95 = 2{,}700 \text{ square inches,}$$

making a total for the 64 poles of 17,200 square inches. According to Equation (**41**) with a constant of 120, the temperature rise will be

$$120 \times \frac{8{,}200}{17{,}200(1 + 0.0002 \times 4{,}150)} = 32^\circ \text{F}.$$

294. Full Load Efficiency.—For the determination of the efficiencies, we have now the following losses:

The iron losses........................	9,700	watts
watts consumed in the armature winding..	8,200	"
excitation watts for cos $\varphi = 0.8$ full load...	8,200	"
and for the friction and ventilation losses we assume	6,000	"
making a total of........................	32,100	watts

The full load efficiency with a power factor of cos $\varphi = 0.8$, will be $\frac{375{,}000}{375{,}000 + 32{,}100} = 92\%$.

295. Half Load Efficiency.—For half load, that is, when the armature winding carries 31.25 amperes, with a power factor of cos $\varphi = 0.8$, the armature loss will be 2,050 watts, and the excitation power 6,000 watts, while the iron and friction losses remain practically unaltered; consequently the half load efficiency is equal to $\frac{187{,}500}{187{,}500 + 23{,}750}$ $= 89$ per cent.

296. Relative Weights of Iron and Copper.—With reference to the data of Table **14**, it is interesting to compare the various weight items of low speed and standard alternators, of equal output.

In Par. **283**, the weight of armature copper is 885 lbs.
“ “ **285**, “ “ “ “ stampings is 5,860 “
“ “ **293**, “ “ “ field copper is 3,250 “

Against these values, the standard type of alternator shows much lower material weights, the total amount of copper being ....1,500 lbs.
while the armature stampings only amount to 3,750 lbs.

It may be pointed out, that the weight of the iron could have been reduced by decreasing the height of the armature core.

297. Weights of Low Speed Alternator.—A comparison is not possible between the castings and auxiliary parts, as in the present case the flywheel weight is placed in the magnet wheel; therefore it is preferable to give a detailed list of material for a low speed alternator as an example.

The armature consists of:

Cast iron shell and shield rings..........	12,880	pounds
armature stampings....................	5,880	“
bolts and nuts........................	728	“
armature copper......................	896	“
micanite insulation and hard wood fixing wedges	112	“
terminal board, brush gear and name plate	1,120	“
Total............................	21,616	“

The magnet wheel consists of:

Cast iron flywheel (rim, hub and arms)...	32,480	pounds
pole stampings........................	3,584	“
bolts and steel wedges for fixing the poles.	2,128	“
field copper..........................	3,360	“
wrought iron and press board magnet bobbins and brass end plates for the coils	392	“
gun metal slip rings and cast iron bracket.	392	“
Total..........................	42 336	“

The total weight of the machine is 63,952 pounds, exclusive of the shaft and bearings, which for such large direct coupled sets are supplied by the engine makers.

The above figures clearly indicate that the idle material of the low speed machines with their large diameter, is considerably increased compared with that of a standard speed alternator.

298. Summary of Design.—In conclusion it should be mentioned, that good regulation and efficiencies could have been obtained more advantageously by applying greater flux and less ampere turns, which would imply a smaller diameter and a larger iron length. It was not possible to comply with this condition, as the specified flywheel effect necessitated a larger diameter. The only improvement which could be made in this particular design, is a slight increase in the flux, so reducing the armature ampere turns, as well as the field turns. With regard to the specific utilization of the materials, it should be pointed out that the density of the flux in the armature core ought to be lower, so making the saturation higher, because the field winding could stand a higher current density than actually used, see Par. **290**.

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THE DESIGN OF ALTERNATING GENERATORS AND SYNCHRONOUS MOTORS.

DESIGN OF A STANDARD SPEED, REVOLVING FIELD TYPE, THREE-PHASE ALTERNATOR.

299. General Specification of Alternator.—The generator, direct coupled to a high speed steam engine, should be capable of delivering 175 KVA. to a power circuit with $\cos \varphi = 0.85$.

The terminal voltage on the star connected armature has to be 220 volts, with a frequency of 40 cycles per second.

The voltage drop should not exceed 4% on a non-inductive full load with $\cos \varphi = 1$, and not exceed 12% on an inductive full load with $\cos \varphi = 0.85$.

The efficiencies should not be less than 91% for inductive full load and 87% for inductive half load.

The temperature rise on any part of the machine should not exceed 75 degrees Fahrenheit, provided that the temperature of the surrounding air is 65 degrees Fahrenheit.

300. Engine Speed.—The engine makers state that the approximate highest speed they can run their engine of $\frac{175 \times 0.85}{0.91 \times 0.746} = 220$ H.P. (see Par. **59**) is 400 R.P.M., which corresponds to a generator with 12 poles (see Equation **7**).

301. Armature Stampings.—From Table 16, a diameter of about 45 inches would be a standard value, but as the next smaller size of stamping, 35.4 inches diameter, is in stock, we will decide to use it, inasmuch as suitable frame patterns are also at our disposal, which may easily be altered in width, according to the necessary armature length.

The standard stamping which will be used, has 36 slots of the dimensions as indicated in Fig. 74.

302.—Pole Pitch and Arc.—The pole pitch is equal to $\frac{35 \times 3.14}{12} = 9.18$ inches, so that with a pole arc ratio of 0.65 we obtain a pole arc equal to $9.18 \times 0.65 = 6$ inches.

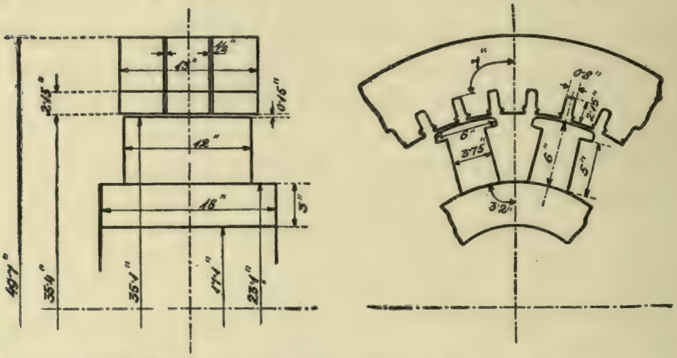


FIG. 74.—175 KVA., 400 REVS., 40-CYCLE, 3-PHASE ALTERNATOR.

For the armature we choose the long type of coil laid in open slots, so that the form factor *k*, of the E.M.F. will be 2.46 (see Table 14).

303. Armature Ampere Conductors.—With reference to Fig. 62, we find that for a capacity of $\frac{175}{400} = 0.44$ KVA. per revolution, the most suitable total flux will be about 43.5×10^6 magnetic lines and the corresponding value of armature ampere conductors is equal to

$$0.44 = (3\,Z \times C) \times 43.5 \times 10^6 \times \frac{2.46}{120 \times 10^{\prime\prime}}$$

where $3\,Z \times C = 49{,}500$, from Equation (**35**).

Now we have to determine whether these ampere turns can be placed inside the slots and on the periphery, without cutting the insulation of the slots too fine, or driving the current density in the conductors too high.

With regard to the specified regulation, which in the present case is a stiff condition, the peripheral density should be kept within the average value, as indicated in Fig. 63.

304. Normal Phase Current.—The normal phase current being $\frac{175.000}{1.73 \times 220} = 460$ amperes, the number of armature conductors to be employed per phase will be $\frac{49.500}{3 \times 460} = 35$, or the nearest number, which is a multiple of the 12 slots available per phase, gives 36 conductors per phase, or 3 per slot. Therefore, the exact value of total ampere conductors will be $3 \times 36 = 108$, and the resulting peripheral density is equal to $\frac{108 \times 460}{35.4 \times 3.14} = 447$ ampere conductors per inch, which is a good figure.

305. Current Density in Armature Winding.—With regard to the low tension of the alternator, an insulation thickness of 0.045 inch micanite is more than sufficient. For the three conductors, the size and shape of the slot is most suitable, if one conductor is composed of 8 parallel connected No. 6 S.W.G. round wires, each having a double cotton covering. As indicated in Fig. 75, the wires may be arranged in 8 layers.

The total sectional area of a conductor is $8 \times 0.02895 = 0.2316$ square inch; the current density will, therefore, be $\frac{460}{0.2316} = 1{,}980$ amperes per square inch, which is a moderate value and will assist in obtaining the specified efficiencies.

306. Magnetic Density in Teeth.—The next step is to fix the iron length with regard to the magnetic density in the teeth, which is on the average to be 75,000 lines, see Fig. 27, in order that the losses therein shall not be excessive.

From Equation (**33**), we obtain for the fixed value of phase conductors, a flux per pole of

$$127 \times 10^8 = 2.46 \times 40 \times 36 \times F_2 \text{ where } F_2 = 3.6 \times 10^6 \text{ lines,}$$

so that the effective teeth section under a pole has to be about $\frac{3.6 \times 10^6}{75{,}000} = 48$ square inches.

307. Length of Armature.—The expression of the sectional area of the teeth per pole is: $\frac{a}{o} \times r \times l = q_t$, where r is the mean thickness of a tooth. In the present case the pole arc a, is fixed as 6 inches; the slot pitch o, is equal to 3.09 inches; the bottom thickness of the tooth is $\frac{9.26}{3} - 0.8 = 2.29$ inches, while at the top it is 2.7 inches, which results in the mean value of 2.5 inches. Consequently the effective iron length l is equal to $\frac{48 \times 3\ 09}{6 \times 2.5}$ $= 9.85$ inches.

Now, taking an additional length of 15 per cent. on account of the paper insulation between the laminations and assuming two ½-inch ventilating ducts, the overall length of the armature will be $9.85 + 1.45 + 1 = 12.3$ inches.

308. Magnetic Density in Armature Core.—The standard length of the frame provides for 13 inches; therefore, we may take the armature overall length as 13 inches, having in view a pole core length of 12 inches, in order to make allowance for the useful leakage.

According to Fig. 26, the magnetic density in the armature core should be about 40,000 lines per square inch. The standard stamping offers, with the fixed length, an effective section of $5 \times 12 \times 0.85 = 51$ square inches, so that the density will be $\frac{3.6 \times 10^6}{2 \times 51} = 35{,}300$ lines per square inch, which is a satisfactory figure.

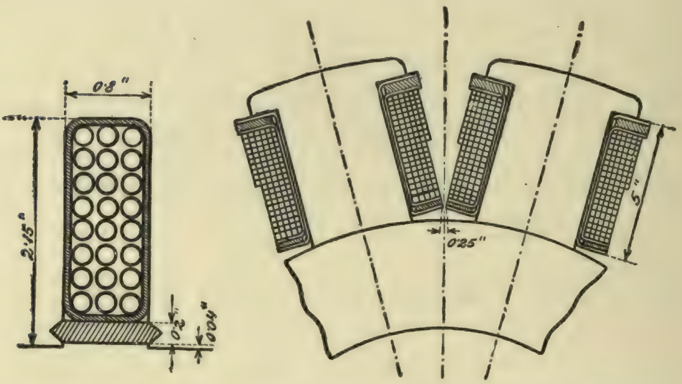
This preliminary calculation indicates clearly that the stamping at our disposal is so far suitable for the present case.

309. Field Winding Space.—We have now to see, if, for the specified conditions of regulation and for the assumed armature ampere turns, the corresponding field ampere turns will have the necessary space. As already pointed out, the bore of the machine is somewhat smaller than the usual value, and as the somewhat stiff condition of voltage drop requires a larger ratio between the armature and field ampere turns than the average one, it is not at all certain that the winding space is large enough. To check this, it is necessary to make several assumptions and calculations, which are afterward to be modified if not found correct.

310. Section of Pole Core.—First of all, it is necessary to design the pole core section such that its saturation shall produce the essential knee or bend in the open circuit characteristic curve. In considering that the voltage drop is to be small and that the power factor is as high as 0.85, it is necessary to drive the saturation of the poles somewhat higher than usual, which affords at the same time, from a mechanical point of view, the advantage that the width of the pole will be diminished, besides affording more space for the winding.

The pole density should be fixed at about 105,000 lines; hence, if we assume a leakage factor σ of 1.3, the necessary effective section is equal to $\frac{1.3 \times 3.6 \times 10^6}{105{,}000} = 44.5$ square inches; and the pole width is $\frac{44\ 5}{12 \times 0.96} = 3.85$ inches, which we make, for convenience, 3.75 inches.

311. Voltage Drop.—The voltage drop being specified as 4% for non-inductive full load and 12% for the cos $\varphi = 0.85$ load, with reference to Fig. 5, we may assume a voltage drop of 18% for an armature current corresponding to the full load, but having a power factor, cos $\varphi = 0$. Provided that the normal open circuit pressure is on the knee of the curve the above cos $\varphi = 0$ regulation will be obtained by making the normal excitation ampere turns about 2.75 times greater than the normal effective back ampere turns of the armature.



FIGS. 75 AND 76.—POLE AND SLOT WINDINGS OF 175 KVA., 220 VOLT, 3-PHASE ALTERNATOR.

312. Field Ampere Turns.—The ampere conductors of the armature have been calculated as 16,560 per phase, so that the number of ampere turns per phase is 8,280 and the effective back ampere turns will be $2.12 \times 8,280 = 17,500$, see Equation (**32**). Therefore, the minimum field ampere turns corresponding to the normal open circuit voltage, are equal to $2.75 \times 17,500 = 48,000$ total, or 4,000 per pole.

313. Winding Space Available.—For this excitation, we will assume a current density of 1,300 amperes per square inch of the field winding and a space factor of 0.4; so with sufficient exactness the total area of one side of a coil may be taken equal to the value: $\frac{4{,}000}{1{,}300 \times 0.4} = 7.7$ square inches. Now, if we limit the winding depth to say 1.5 inches, then the height of the coil will be $\frac{7.7}{1.5} = 5$ inches, see Fig. 76, from which it will be seen that the available winding space is sufficient.

314. Preliminary Dimensions.—Having ascertained that the choice of the iron and copper sources and that of the leading dimensions, Fig. 74, will permit the execution of a successful design, it is necessary to base the calculations on the preliminary dimensions as follows:

Bore of the armature	35.4	inches;
external diameter of the armature	49.7	" ;
slot width	0.8	" ;
" depth	2.15	" ;
overall length of the armature with two ½-inch ducts	13	" ;
pole arc	6	" ;
pole core width	3.75	" ;
" length	12	" ;
total pole height	6	" .

The cast iron rim should have a section such that it should have a saturation degree which will essentially contribute to the number of field ampere turns.

In accordance with Fig. 74, this section is dimensioned to have an area of 3 × 18 = 54 square inches, which will produce a density of about 43,500 lines per square inch.

315. Air Gap.—The correct choice of the air gap in the first instance will greatly shorten the calculations, and the best method of fixing the same will be to determine the normal ampere turns of the field, as indicated in Par. **312**. Assume that about 70% of the ampere turns are utilized for

TABLE 19.

E. M. F.				260		220		180		140	
Armature Flux.				4.25×10^6		3.6×10^6		2.95×10^5		2.3×10^6	
Field Flux.				5.45×10^6		4.6×10^6		3.77×10^6		2.95×10^6	
Material and Sectional Area of:	Wheel Rim.	Cast Iron. 54	Magnetic Densities and Corresponding Ampere Turns per one inch length.	50,500	170	42,500	110	35,000	75	27,400	44
	Pole Core.	0.04″ Sheet 43		126,000	450	106,000	135	87,000	43	68,000	21
	Teeth.	0.02″ Sheet 49		86,500	42	73,500	26	60,000	16	47,000	10
	Armature Core.	0.02″ Sheet 51		41.600	7	35,300	6	29,000	5	22.500	4
Length of Magnetic Paths.	Wheel Rim.	3.2″	Ampere Turns of the Paths.	545		350		240		140	
	Pole Core.	5		2,250		675		215		105	
	Teeth.	2.15		90		56		35		22	
	Armature Core.	7		50		42		35		28	
r_0		$\frac{8}{10^4}$		3,400		2,875		2,360		1,840	
Total Ampere Turns Per Pole.				6,335		3,998		2,885		2,135	

the air leakage paths, that is, in the present case, 4,000×.70 = 2,800 ampere turns. Then, for the first approximation, take the air section equal to the product of pole arc and pole core length, so that the value of air path ampere turns may be taken for

$$2{,}800 = \frac{\delta \times 0.313}{6 \times 12} \times 3.6 \times 10^6 = \delta \times 15{,}700.$$

For the particular design in question, the result of the above equation will be an air gap δ of 0.176 inches. We, therefore, base our detailed calculation on a gap value of 0.15 inch.

316. Leakage Factor.—For the exact determination of the no-load characteristic, we have all the data except the leakage factor, which, according to Par. **154**, will be

$$\sigma = 1 + \frac{r_0}{r_1'} = 1 + \frac{8}{35.5} = 1.23,$$

since $$r_0 = \frac{0.313}{\frac{12 \times 6 \times 2.29}{3.09 \times 0.15} + \frac{12 \times 6 \times (0.2 + 0.4)}{3.09 \times (0.2 + 0.15)}} = \frac{8}{10^4},$$

and $$r_1' = \frac{0.313}{\frac{4 \times 1 \times 12}{3.1} + \frac{4 \times 12 \times 5}{3.85} + \frac{4 \times 3.75 \times 5}{7.6}} = \frac{35.5}{10^4}.$$

317. Characteristic Curves.—In Table 19 the different data is collected and four points of the no-load characteristic determined. So far the results are satisfactory, because the normal voltage comes at the knee and the curve part above this point is not too flat; and, further, because the value of the normal field ampere turns is close to that which we had in view. For the form of the characteristic see Fig. 77.

318. Short Circuit Characteristic.—To effect the determination of the short circuit characteristic the factor k_s has to be calculated.

The reluctance r_2^1 is equal to

$$\frac{0.313}{\frac{4 \times 2.15 \times 12 \times 3.1}{0.8 \times 9.3} + \frac{4 \times 2.15 \times 2.3 \times (9.3 + 3.1)}{9.3 \times 3.1} + 15} = \frac{47.5}{10^4}.$$

For the factor we find a value of $1 + \frac{r_0}{r_2^1} = 1 + \frac{8}{47.5} = 1.17$, say, $1.2 = k_s$. That is, for the normal armature current which represents a back ampere turn value of $\frac{17{,}500}{12} =$ 1,450 per pole, the corresponding excitation will be equal to $1.2 \times 1{,}450 = 1{,}740$ ampere turns. The straight line through the zero and this particular point, *B*, represents the short circuit characteristic, see Fig. 77.

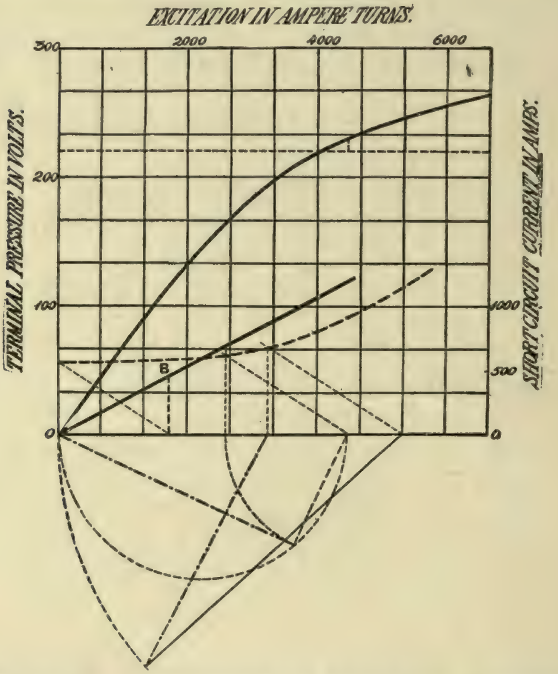


FIG. 77.—CHARACTERISTICS OF THE 175 KVA., 400 REVS., 40-CYCLE, 3-PHASE ALTERNATOR.

319. Calculation of Drops.—In Fig. 77, the application of the graphical method in determining the non-inductive and $\cos \varphi = 0.85$ full load voltage drops, gives satisfactory results.

In the first case, see Par. **299**, a 4 per cent. drop is specified and in the present design 4 per cent. is obtained.

In the second condition, the specified drop is 12 per cent., whereas the calculated drop amounts to 12.3 per cent.

From the above it is evident that the most difficult part of electrical design is successfully achieved and there is no difficulty in obtaining the specified efficiencies and temperature rise, which are simply average values.

320. Calculation of Field Winding.—In accordance with the data of Fig. 77, the maximum excitation per pole is equal to $Z \times C = 5{,}340$ ampere turns; or, total for all the poles, $2p \times Z \times C = 12 \times 5{,}340 = 64{,}080$ ampere turns.

The field winding has to be calculated for a pressure of 65 volts at its terminals, in order to obtain the necessary maximum ampere turns.

The above condition can be expressed by the equations, $65 = 64{,}080 \frac{L}{q} \times \frac{8}{10^7}$, and $64{,}080 = 2p \times Z \times C$, where L is the mean length of field turn and q the sectional area of a conductor.

321. Section of Conductors.—Assuming a total winding depth of 1.5 inches, a rough sketch indicates a length of mean turn L, equal to 36 inches; consequently the conductor section is equal to $q = \frac{64{,}080}{65} \times 36 \frac{8}{10^7} = 0.0285$ square inch.

The nearest wire to this section is a No. 6 S.W.G. of 0.02895 square inch.

For the maximum excitation, we will allow a current density of 1,700 amperes per square inch, so that the corresponding current will be $0.02895 \times 1{,}700 = 49$ amperes, and the number of turns per pole $\frac{5{,}340}{49} = 110$, which may be arranged as indicated in Fig. 76, the number of layers being 5 and 6 and the total depth 1.4 inches.

The maximum excitation voltage is 65 volts and the current 49 amperes, so that the maximum excitation energy will be $65 \times 49 = 3{,}180$ watts.

322. Temperature Rise.—The temperature rise in the field coils is equal to

$$T_1 = 120 \frac{3{,}180}{(1+0.0002 \times 3{,}050)3{,}660} = 65° \text{ F}.$$

The peripheral speed on the average is $\frac{29 \times 3.14 \times 400}{12} =$ 3,050 feet per minute and the cooling surfaces consist of the cylindrical surfaces of $12 \times 5 \times 43 = 2{,}580$ square inches, and end faces of $24 \times 12 \times 3.75 = 1{,}080$ square inches, making a total of................3,660 square inches.

323. Armature Copper Loss.—In order to investigate the heating conditions of the armature it is necessary to calculate the various losses. The length of mean armature turn, as actually measured, is equal to 56 inches, consequently the length of all the turns in series is $18 \times 56 = 1{,}008$ inches per phase.

The hot resistance of a phase winding will be $\frac{1{,}008}{8 \times 0.02895} \times \frac{8}{10^7} = 0.0035$ ohm; and, therefore, the maximum armature copper loss at full load is equal to $3 \times 460^2 \times 0.0035 = 2{,}200$ watts, in all three phases.

324. Loss in Teeth.—The weight of the teeth iron being $36 \times 2.5 \times 2.15 \times 12 \times 0.85 \times 0.28 = 580$ pounds, and the saturation 73,500 lines per square inch, there will be an energy loss of $580\ (3.5 \times 0.6) = 2{,}370$ watts.

325. Loss in Core.—The armature core above the slots has a weight of $\frac{49.7^2 - 35.4^2}{4} \times 3.14 \times 12 \times 0.85 \times 0.28 = 2{,}900$ pounds; the saturation is 35,300 lines per square inch and the resulting hysteresis and eddy current losses are 4,150 watts.

326. Total Armature Losses and Temperature Rise.—The total armature losses amount to 8,720 watts, for which the cooling surface is 9,050 square inches, composed of the internal and external cylindrical surfaces and six side faces.

According to Equation (**40**), the resulting temperature rise is equal to $T_2 = 75 \times \frac{8,720}{9,050} = 72°$ F., which is below the specified temperature rise of 75° F., see Par. **299**.

327. Full Load Efficiency.—In previous paragraphs, the following losses have been calculated, from which the efficiencies may be found.

Armature copper loss at inductive full load....	2,200	watts;
armature iron losses........................	6,520	" ;
the corresponding excitation energy........	3,180	" ;
and an allowance for the friction and ventilation losses of..........................	3,800	" ;
making a total of.........................	15,700	watts.

The full load efficiency, with the total loss of 15,700 watts, is equal to $\frac{175,000}{175,000 + 15,700} = 92$ per cent., which is slightly higher than that specified, see Par. **299**.

328. Half Load Efficiency.—With half load the iron and friction losses remain the same as on full load while the armature copper loss is equal to 550 watts and the excitation energy 2,450 watts; this latter value being obtained by simple interpolation between the maximum and minimum excitation losses.

The half load efficiency, which is not of great importance, is also satisfactory, being $\frac{87,500}{87,500 + 13,320} = 87$ per cent.

329. Summary of Design.—The regulation of the present alternator is better than the average of standard machines.

The weights of the copper and armature stampings compare favorably with those of a corresponding standard generator, while the weight of iron material is larger and that of copper considerably less.

The output constant for the alternator in question is found equal to $\frac{D^2 \times l \times N}{KVA.} = \frac{35.4^2 \times 12 \times 400}{175} = 34 \times 10^3$ which points to a successful design, as regards economy in dimensions.

DESIGN OF A 25-CYCLE REVOLVING FIELD TYPE THREE-PHASE ALTERNATOR.

330. General Specification of Alternator.—The 25-cycle 300 KVA. three-phase generator, which has to supply a power circuit under a line pressure of 500 volts, shall fulfil the following conditions:

The power factor of the circuit is assumed to be 0.8; the voltage drop at full load shall not be more than 20 per cent.; the full load efficiency must be at least 93 per cent., and the temperature rise shall not exceed 75° F.

331. Speed.—After consulting the engine makers, it has been decided to run the alternator at a speed of 375 revolutions per minute. The corresponding number of poles for that speed will be 8.

332. Number of Slots.—With reference to Fig. 62, the most suitable flux will be found to be about 56×10^6, the ratio $\frac{KVA.}{N}$ being equal to 0.8.

From Equation (**35**), the corresponding value of armature ampere conductors is equal to $3\,Z \times C = 78{,}000$.

We will allow about 1,000 ampere conductors to be placed in a slot, so the number of slots should be about $\frac{78,000}{1,000} = 78$.

The number of poles being 8 and the phases 3, the possible nearest value is 72; therefore, we decide on 3 slots per pole and phase.

333. Conductors per Slot.—The normal current per phase in the star connected armature is equal to $\frac{300,000}{1.73 \times 500} = 346$

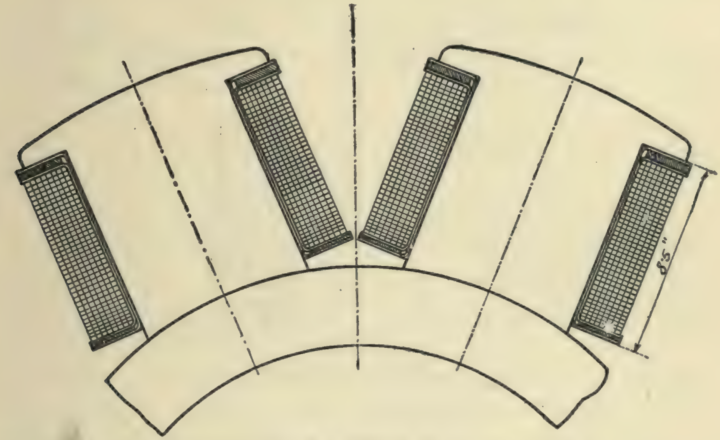


FIG. 78.—POLE WINDING 300 KVA., 500 VOLT, 3-PHASE ALTERNATOR.

amperes; therefore, the total number of armature conductors will be $\frac{78,000}{346} = 225$, or the nearest figure which is a multiple of the slot number 72, gives the value of conductors to be applied, as 216; that is, each slot will receive $\frac{216}{72} = 3$ conductors.

334. Size of Bore.—For the choice of size of the bore, it is necessary to consult the data of Fig. 63, which gives the average values of peripheral densities. With the foregoing assumptions, we have found that the total number of armature ampere conductors will be 346 × 216 = 74,600 and, allowing a peripheral density of 500 ampere conductors per inch, the approximate value of the bore is equal to $\frac{74\,600}{500 \times 3.14} = 47.5$ inches. If the diameter of the wheel, Fig. 78, is fixed as 47 inches, then the peripheral speed will be 4,600 feet, which is a good average value.

335. Dimensions and Shape of Slots.—The dimensions of the slots and their shape are to be so designed that a high space factor may be obtained. With regard to the size of conductor, we assume a current density of about 2,000 amperes, so that in the present case, a sectional area of $\frac{346}{2,000} = 0.173$ square inches is required.

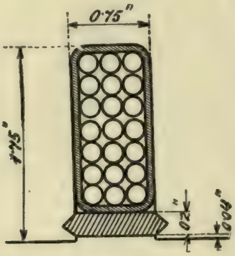


FIG. 79.—SLOT WINDING, 300 KVA., 500 VOLT, 3-PHASE ALTERNATOR.

Each slot has to receive 3 conductors; therefore, it will be best to use several wires in parallel, to make up a conductor. It is found that 7 No. 7 S.W.G. round wires give the most satisfactory result, as regards the current density and slot shape.

A slot with the dimensions of 0.75 inch in width and 1.75 inches in depth, takes the 21, No. 7 S.W.G. wires, the 0.05 inch thick micanite insulation, and leaves a margin on account of the uneven assembling of the stampings, as well as a certain play for the former wound coils.

The double cotton covered wires arranged in 7 layers, fill out the slot, and produce a space factor of $\frac{0.51}{1.32} = .38$.

The ratio between the slot depth and width is $\frac{1.75}{0.75} = 2.35$, see Fig. 79.

336. Thickness of Teeth.—The thickness of the teeth has to be determined next.

The internal periphery of the armature is equal to $47.5 \times 3.14 = 149$ inches; the slot pitch o is equal to $\frac{149}{72} = 2.07$ inches; the narrowest part of the tooth is $2.07 - 0.75 = 1.32$ inches and the mean thickness will be found equal to 1.4 inches.

337. Pole Pitch and Arc.—The determination of the effective armature length is the next step.

The number of cycles being 25, we will allow in the first approximation a magnetic density in the teeth of 95,000 lines per square inch, which implies a hysteresis and eddy current loss of 3.7 watts per pound of iron, this being a good average value.

To proceed in the indicated manner, we have to fix at first, the pole arc. Provided that the diameter is 47 inches, the pole pitch will be equal to $\frac{47 \times 3.14}{8} = 18.45$ inches, and assuming a pole arc ratio of 0.65, the arc length will be 12 inches.

338. Length of Armature.—The number of slots per phase and pole being 3 and the pole arc ratio 0.65, the form factor k will be equal to 2.26 and from Equation (**33**) the useful flux is equal to

$$10^8 \times \frac{500}{1.73} = 2.26 \times 25 \times 24 \times 3F_2, \text{ where } F_2 = 7.1 \times 10^6.$$

The ratio $\frac{F_2}{B_t}$ indicates that the teeth section under a pole must be equal to $\frac{7.1 \times 10^6}{95,000} = 75$ square inches, and consequently the armature length will be $\frac{75}{0.9 \times \frac{12}{2.07} \times 1.4}$ $= 10.3$ inches, including the paper insulation. After two half-inch ventilating ducts are provided, the overall length may be taken as 12 inches.

339. Height of Core.—For the determination of the armature core height, a magnetic density of 47,000 lines per square inch should be taken, see Fig. 26, and accordingly the iron above the slots will be fixed as 7.5 inches.

340. Particulars of Pole Pieces.—When designing the pole pieces, the pole shoe height should be taken as 1.25 inches and the length of the pole core as 11 inches.

Assuming an average leakage factor σ, of 1.25 and a pole core density of 105,000, the pole core section should be $\frac{8.85 \times 10^6}{105,000} = 85$ square inches and the pole width $\frac{85}{11 \times 0.96}$ $= 8.0$ inches.

The material of the wheel rim in the present design should be cast steel, with a section of 3.1 by 18.5 inches, resulting in a saturation of $\frac{8.85 \times 10^6}{2 \times 57} = 77,000$ lines per square inch.

For the determination of the pole core height it is necessary in the first instance to procure the approximate value of the field ampere turns per pole, and calculate the space occupied by them.

341. Armature Ampere Conductors.—The number of total armature ampere conductors has been fixed as 74,600 and the value of the back ampere turns is equal to $2.12 \times 12,430 = 26,200$.

With regard to the specified voltage drop, which is an average figure, the value 2.0 is assumed as the ratio between the total field ampere turns, corresponding to the normal open circuit voltage and the normal armature back ampere turns. Consequently the poles have to provide for 52,400 ampere turns, or each pole has to carry a normal value of 6,500 ampere turns.

342. Field Winding.—In all probability, the depth of the field winding will be very close to the upper limit of 2 inches; therefore, we will not allow a greater current density than 1,000 amperes per square inch.

Assuming an average space factor of 0.4, including the space taken up by the bobbins and end plates, the necessary winding space is equal to $\frac{6,500}{1,000 \times 0.4} = 16$ square inches.

Fig. 78 shows that with a pole height of 8.5 inches sufficient space is obtained for the winding.

343. Principal Dimensions.—The principal dimensions of the machine in question are as follows:

Bore of armature	47.5	inches	;
external diameter of armature core	65.5	"	;
slot width	0.75	"	;
slot depth	1.75	"	;
overall length of armature, including two ½-inch ducts	12	"	;
pole core length	11	"	;
pole arc	12	"	;
pole core width	8	"	;
pole core height	8.5	"	;
wheel rim length	18.5	"	;
wheel rim height	3.1	"	.

These dimensions are subject to slight alterations, as detailed calculation may require, see Fig. 80.

344. Air Gap.—For the approximate determination of the air gap, we will assume that the no-load characteristic will take a form such, that for the normal or otherwise minimum excitation, 70 per cent. of the total ampere turns shall be consumed in the air gap.

In the present case the gap ampere turns will be equal to $6{,}500 \times 0.7 = 4{,}550$.

The useful flux being 7.1×10^6, and the air section about $12 \times 11 = 132$ square inches, we find that in the first approximation, by means of the equation, $6{,}550 = \frac{\delta \times 0.313}{132} \times 7.1 \times 10^6$ the air gap must have a value close to 0.27 inch. For further calculations it will be taken as 0.25 inch.

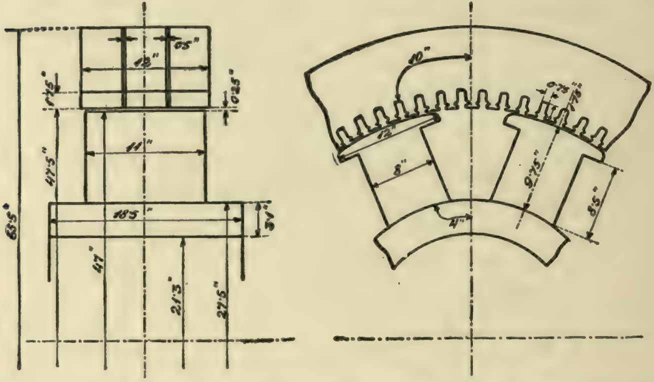


Fig. 80.—300 KVA., 375 Revs., 25-Cycle, 3-Phase Alternator.

345. Open Circuit Characteristic.—In determining the open circuit characteristic, the leakage factor σ is equal to 1.25, because

$$r_0 = \frac{0.313}{\frac{12}{2.07} \times \frac{1.32 \times 11}{0.25} + \frac{12}{2.07} \times \frac{11(0.22+0.38)}{0.22+0.25}} = \frac{7.4}{10^4},$$

and

$$r_1' = \frac{0.313}{\frac{4 \times 1.25 \times 11}{6.5} + \frac{4 \times 8.5 \times 11}{6} + \frac{4 \times 8.5 \times 8}{14}} = \frac{35}{10^4}.$$

TABLE 20.

E. M. F.				600		500		400		300	
Armature Flux.				8.5×10^6		$7\ 1 \times 10^6$		5.7×10^6		4.25×10^6	
Field Flux.				10.6×10^6		$8\ 9 \times 10^6$		7.1×10^6		5.3×10^6	
Material and Sectional Area of:	Wheel Rim.	Cast Steel. 57	Magnetic Densities and Corresponding Ampere Turns per Inch Length.	93,000	58	77,500	30	62,000	17.5	46,500	10
	Pole Core.	0 04″ Sheet. 85		120,000	435	105 000	130	88,500	45	62,500	18
	Teeth.	0 02″ Sheet. 80		106,000	135	89,000	46	71,000	23	53,000	11
	Armature Core.	0.02″ Sheet 75		56,500	14	47,300	10	38,000	8	28,500	6
Length of Magnetic Paths.	Wheel Rim.	4	Ampere Turns of the Paths.	232		120		70		40	
	Pole Core.	8.5		3,700		1,100		380		150	
	Teeth.	1.75		238		80		40		20	
	Armature Core.	10		140		100		80		60	
r_0		7.4 10^4		6,300		5,250		4,200		3,150	
Total Ampere Turns per Pole.				10,610		6,650		4,770		3,420	

The complete calculation of the open circuit characteristic is embodied in Table 20, and its result is given in Fig. 81.

346. Short Circuit Characteristic.—The constant of the short circuit characteristic k_s will be found equal to

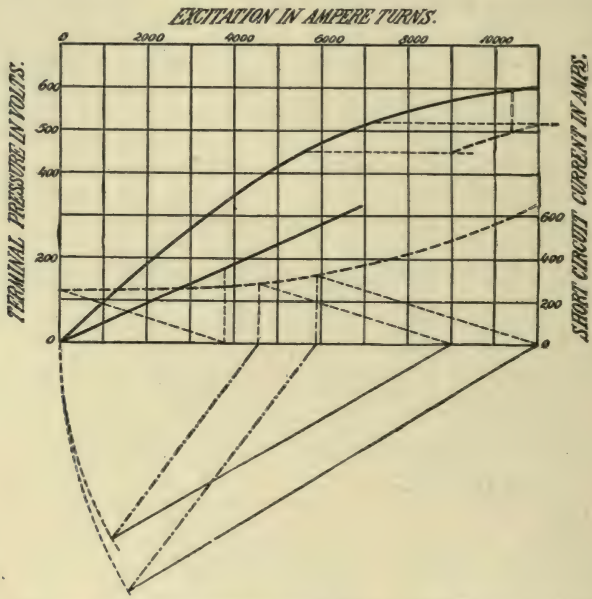


FIG. 81.—CHARACTERISTICS OF 300 KVA, 375 REVS., 25-CYCLE, 3-PHASE ALTERNATOR.

$1 + \frac{7.4}{61} = 1.12$, say, 1.15, r_o being calculated as $\frac{7.4}{10^4}$, and

$$r_2^1 = \frac{0.313}{\frac{4 \times 1.75 \times 12 \times 2.07}{0.75 \times 18.5} + \frac{4 \times 1.75 \times 1.32(18.5 + 2.07)}{18.5 \times 2.07} + 34} = \frac{61}{10^4};$$

that is, the normal current will appear in the short circuited armature for an excitation of 26,200 × 1.15 = 30,000 total ampere turns, or 3,750 ampere turns per pole, see Fig. 81.

347. Load Characteristic.—The determination of the load characteristic indicates that the specified condition of voltage drop is satisfactorily complied with, though a reduction of the air gap to 0.24 inch would make the agreement still closer.

348. Particulars of Field Winding.—From Fig. 81 we obtain a maximum value of field ampere turns per pole equal to 10,200 ampere turns, while the corresponding excitation voltage on the slip rings is specified as 120 volts.

For the maximum excitation we will allow a current density in the field winding of 1,400 amperes per square inch.

Therefore, the number of turns and size of wire may be calculated as follows:

$$120=\frac{L_1\times Z\times C_1\times 2p}{q}\times\frac{8}{10^7}=\frac{L_1\times 10{,}200\times 8}{q}\times\frac{8}{10^7}=0.0255.$$

The length of mean turn is equal to 47 inches, so that the conductor section will be 0.0255 square inches, or with the nearest standard wire, No. 7 S.W.G., 0.0243 square inch. With this value the current is equal to $0.0243\times 1{,}400=34$ amperes and the turns per pole to $\frac{10{,}200}{34}=300$.

349. Temperature Rise.—The resistance of all the coils in series is equal to $\frac{300\times 8\times 47}{0.0243}\times\frac{8}{10^7}=3.7$ ohms, and the maximum current is 34 amperes; therefore, the maximum energy consumption will be $34^2\times 3.7=4{,}300$ watts.

The temperature rise will be 60° F., as the cooling surface is equal to 5,100 square inches, and the mean value of the peripheral speed, 3,500 feet per minute.

350. Armature Losses.—The armature winding has a length of mean turn of 92 inches and a resistance per phase of $\frac{36\times 92}{7\times 0.02433}\times\frac{8}{10^7}=0.0156$ ohm; therefore, with the normal current, the energy loss will be $346^2 \times 0.0156 = 1,866$ watts per phase, or 5,600 watts total.

351. Loss in Teeth.—The weight of the teeth iron is $72 \times 11 \times 1.4 \times 1.75 \times 0.9 \times 0.28 = 490$ pounds, and the normal saturation being 89,000 lines per square inch, there will be a hysteresis loss of $490 \times 3 = 1,470$ watts and an eddy current loss of $490 \times 0.35 = 170$ watts.

352. Loss in Core.—The weight of armature core is equal to

$$\frac{66^2 - 51^2}{4} \times 3.14 \times 11 \times 0.9 \times 0.28 = 3,900 \text{ pounds.}$$

The losses due to hysteresis and eddy currents are equal to 1.15 watts per pound of iron, at a density of 47,300. Therefore, the total loss in the core is equal to $3,900 \times 1.15 = 4,500$ watts.

353. Cooling Surface and Temperature Rise.—The cooling surface consists of:

The inner cylindrical surface......	1,800	square inches,
the external cylindrical surface.....	2,400	" "
six side faces......................	9,900	" "
making a total of.............	14,100	square inches.

From the above the temperature rise will be

$$75 \times \frac{11,740}{14,100} = 63^\circ \text{ F.}$$

354. Efficiency.—Assuming a value of 5,400 watts for losses caused by friction and ventilation, the full load efficiency of the alternator will be

$$\frac{300.000}{300,000+5,600+6,140+4,300+5,400} = 93.4 \text{ per cent.},$$

which is somewhat better than specified, see Par. **330**, but as there is always a sort of uncertainty in the calculation of the same, no alteration should be made in the design, which proves to be in accordance with the specification.

355. Summary of Design.—The economy in the principal dimensions may be indicated by the value of the output constant, which is $\frac{47.5^2 \times 11 \times 3.75}{300} = 31 \times 10^3$.

The amount of copper used in the field is........ 835 lbs.
the amount of copper used in armature is...... 510 "
the weight of the armature stampings is....... 4,400 "
which, compared with the data of Fig. 14, shows the proper specific utilization of the respective materials.

DESIGN OF A REVOLVING FIELD TYPE SINGLE-PHASE ALTERNATOR.

356. General Specification of Alternator.—This high tension single phase alternator must be capable of supplying a lighting circuit at a frequency of 60.

The capacity of the machine must be 520 KVA., the power factor of the line and transformers being assumed as 0.95.

The working voltage required is 2,800 volts; the voltage drop on a non-inductive full load should not exceed 6 per cent.; the full load efficiency should not be less than 93 per cent., and the maximum temperature rise in any part of the machine should not exceed 80° F.

357. Arrangement of Winding.—The prime mover being a steam engine direct coupled to the alternator, the speed is fixed at 300 revolutions per minute, therefore, the alternator will have $\frac{60 \times 60}{300} = 12$ pairs of poles, which is equal to 24 poles.

With regard to the proper distribution of the winding to obtain a sinusoidal wave form, we take an armature core with 6 slots per pole, but only 4 of them to contain the armature winding, while two are left empty. The slots should be open and the coils former wound.

The winding applied is illustrated in Fig. 82, and the ratio between the coil breadth and pole pitch in the present case is one-half.

For the pole arc ratio we choose a value of 0.6, so that the form factor will be equal to 2.2, see Table 14.

358. Diameter of Bore.—For the choice of diameter of bore the data in Table 16 gives in this particular case satisfactory values. The 520 KVA., 300 revs., 60-cycle single phase alternator under discussion, corresponds to a 750 KVA., 50-cycle polyphase generator, which has a bore of 84 inches. Taking into consideration that the number of poles is 24, against 20 of the polyphase machine, an armature bore of 87.5 inches will be found very suitable.

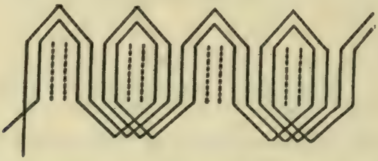


Fig. 82.—Winding Diagram of 520 KVA., Single Phase Alternator.

Neglecting the small difference between the armature bore and wheel diameter, the peripheral speed is equal to

$$\frac{87.5 \times 3.14}{12} 300 = 6{,}850 \text{ feet per minute.}$$

359. Armature Conductors.—The division of the iron and copper sources may be effected by means of Fig. 62, in choosing a flux value which corresponds to an output of about 30 per cent. higher than that of the single phase alternator.

In the present case a total flux is taken, corresponding to $\frac{1.3 \times 520}{300} = 2.25$, equal to 87.5×10^6 lines.

Therefore, the number of armature conductors is equal to $\frac{520}{300} = Z \times C \times 87.5 \times 10^6 \times \frac{2.2}{120 \times 10^{11}}$ where $Z \times C =$ 108,000.

The normal full load current being $\frac{520{,}000}{2{,}800} = 186$ amperes, the number of armature conductors will be $\frac{108{,}000}{186} = 580$.

The nearest figure to 580 which is a multiple of $24 \times 4 = 96$

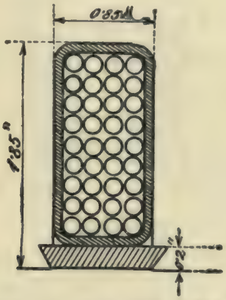


FIG. 83.—SLOT WINDING OF THE 520 KVA., 2,800 VOLT, SINGLE PHASE ALTERNATOR.

slots, is $96 \times 6 = 576$, which gives 6 conductors per slot.

With the above data, the value of ampere conductors per one inch periphery works out as the average value of $\frac{576 \times 186}{87.5 \times 3.14} = 395$.

360. Particulars of Slots—The number of conductors per slot is 6 and the normal current 186 amperes, so each slot will take 1,116 ampere conductors, which, with the proper design of the slot, is an easy matter.

In the determination of the slot form, we have to fix the current density in the conductor, the number of wires per conductor and the thickness of the slot insulation.

Allowing 0.06 inch micanite slot insulation, 0.02 inch for play and a suitable amount for any irregularity of the stampings inside the slots, it will be found that a slot of 0.85 × 1.85 inches will be ample for the 6 conductors, each composed of 6 parallel connected No. 9 S.W.G. wires, assuming a current density of 1,900 amperes per square inch, see Fig. 83.

The total number of slots being 144, the slot pitch is equal to $\frac{87.5 \times 3.14}{144} = 1.91$ inches and the narrowest part of a tooth is equal to $1.91 - 0.85 = 1.06$ inches. while the mean thickness is 1.1 inches.

361. Length of Armature.

361. Length of Armature.—From the basis of the magnetic density in the teeth, we obtain an armature iron length of $\frac{3.7 \times 10^6}{70{,}000 \times \frac{6.8}{1.91} \times 1.1} = 13.2$ inches, corresponding to a flux value of $10^8 \times 2{,}800 = 2.2 \times 60 \times 576 \times F_2$, where $F_2 = 3.7 \times 10^6$ per pole.

With the additional 10 per cent. for the paper insulation and 1 inch for two ventilating ducts, the overall length of the armature will be 15.5 inches.

According to Fig. 26, the saturation of the armature core should be about 30,000 lines and with an iron height of 4.4 inches above the slots, a density of 32,000 lines per square inch is obtained.

362. Particulars of Pole System.

362. Particulars of Pole System.—In designing the pole section, we assume an average leakage factor σ of 1.30, that is, the field flux is taken equal to 4.8×10^6 lines, and with a pole core density of 105,000, the sectional area will be $\frac{4.8 \times 10^6}{105{,}000} = 45.7$ square inches.

Allowing 1.25 inches for the useful leakage, the length of the core is 14.25 inches and, therefore, the pole width will be equal to $\frac{45.7}{14.25 \times 0.95} = 3.5$ inches.

The material of the wheel rim is cast iron, which must be of ample section, of sufficient mechanical strength and so designed as to produce the necessary flywheel effect. Therefore, to comply with the above requirements, the section of the rim should be 20 by 4.75 inches.

In this particular case there is a suitable die for the pole stampings, so, for the sake of convenience, we adopt the dimensions of 3.5 by 8.25 inches. From previous designs of the present type of machine it is known that the available winding space is ample, see Fig. 84.

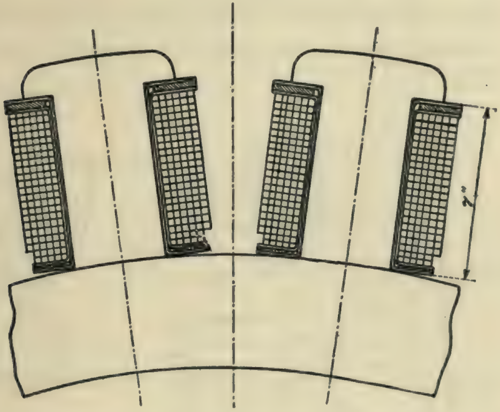


FIG. 84.—POLE WINDING OF 520 KVA., 2,800 VOLT, SINGLE PHASE ALTERNATOR.

363. Ampere Turns and Air Gap.—Corresponding to the specified regulation and considering the degree of iron saturation, we allow a ratio of 2.5 to 1 between the ampere turns of the field and of the armature.

The value of the armature back ampere turns is $0.9 \times \frac{576 \times 186}{2} = 48{,}500$. Therefore, the amount of the total field ampere turns will be $2.5 \times 48{,}500 = 121{,}250$; or, $\frac{121{,}250}{24} = 5{,}050$ ampere turns per pole.

Assuming that 70 per cent. of the field ampere turns are utilized in the air gap, the latter is equal to $0.7 \times 5{,}050 = \frac{\delta \times 0.313}{6.8 \times 14.25} \times 3.7 \times 10^6$, where $\delta = 0.3$ inch.

As the value $\delta = 0.25$ is very close to the correct value, it is used in the calculations of this particular machine.

364. Dimensions of Magnetic Circuit.—The principal dimensions of the magnetic circuit are as follows, see Fig. 85:

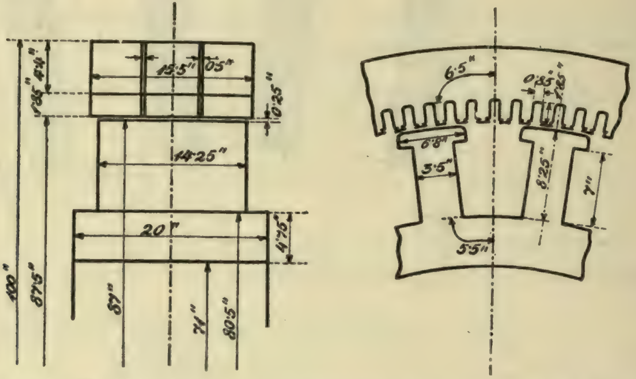


FIG. 85.—MAGNETIC CIRCUIT DIMENSIONS OF 520 KVA., 300 R. P. M., 60-CYCLE, SINGLE PHASE ALTERNATOR.

External diameter of the armature	100	inches
bore of the armature	87.5	"
slot width	0.85	"
slot depth	1.85	"
overall length of the armature, including two ½-inch ducts	15.5	"
external diameter of the magnet wheel	87	"
pole core length	14.25	"
pole arc	6.8	"

pole width	3.5	inches.
pole height (total)	8.25	"
wheel rim height	4.75	"
wheel rim length	20	"

365. Leakage Factor.—In calculating the leakage factor, the gap reluctance is equal to:

$$r_0=\frac{0.313}{14.5\times\frac{6.8}{1.91}\times\frac{1.06}{0.25}+14.5\times\frac{6.8}{1.91}\times\frac{0.3+0.42}{0.2+0.25}}=\frac{10.2}{10^4}.$$

The reluctance of the field leakage path is:

$$r_1'=\frac{0.313}{4\times 14.25\,\frac{1.25}{4.6}+\frac{4\times 7\times 14.25}{6.7}+\frac{4\times 7\times 3.5}{10.2}}=\frac{37}{10^4}.$$

The leakage factor is: $\sigma=1+\frac{10.2}{37}=1.275$,

or with a slight percentage for correction, 1.30.

In Table 21 the calculated results of the no-load characteristic are collected. and in Fig. 86 the corresponding curve is shown.

366. Short Circuit Characteristic.—The constant of the short circuit characteristic is equal to $k_s=1+\frac{r_0}{r_2^1}=1.16$, say, 1.2, where r_0 is equal to $\frac{10.2}{10^4}$, and

$$r_2^1=\frac{0.313}{\frac{4\times 1.85\times 14.5\times 1.91}{11.4\times 0.85}+\frac{4\times 1.85\times 1.1\times(11.4+1.91)}{11.4\times 1.91}+23}=\frac{63}{10^4}.$$

Therefore, the field ampere turns which correspond to the normal short circuit current are 49,500 × 1.2 = 59,500 total, or $\frac{59{,}500}{24}=2{,}500$ ampere turns per pole.

367. Current Density in Field Winding.—The graphical method of determining the voltage drop gives a satis-

TABLE 21.

E. M. F.				3,200		2,800		2,000		1,000	
Armature Flux.				4 25 × 10^6		3.7 × 10^6		2.65 × 10_6		1.32 × 10^6	
Field Flux.				5.5 × 10^6		4.8 × 10^6		3.42 × 10^6		1.71 × 10^6	
Material and Sectional Area of:	Wheel Rim.	Cast Iron. 95	Magnetic Densities and Corresponding Ampere Turns per One Inch Length.	29,000	52	25,000	40	18,000	27	9,000	13
	Pole Core.	0 04″ Sheet. 46		120,000	350	105,000	130	75,000	30	38,500	10
	Teeth.	0.02″ Sheet. 51		83,000	40	72,500	28	52,000	15	26,000	6
	Armature Core.	0 02″ Sheet. 58		36,500	8	32,000	7	22,800	5	11,400	2.5
Length of Magnetic Paths.	Wheel Rim.	5.5	Ampere Turns of the Paths.	285		220		120		72	
	Pole Core.	7		2,440		910		210		70	
	Teeth.	1 85		75		52		28		12	
	Armature Core.	6.5		52		45		32		15	
r_0		$\frac{10.2}{10^4}$		4,340		3,760		2,700		1,350	
Total Ampere Turns per Pole.				7,192		4,987		3,090		1,529	

factory result, see Fig. 86. The maximum number of field ampere turns required is 6,000 × 24 = 144,000.

The excitation voltage is specified as 160 volts.

The coils, possessing ample winding space, we will allow a maximum current density of 1,600 amperes per square inch; consequently, the conductor section will be equal to

$$160 = 144{,}000\,\frac{L}{q} \times \frac{8}{10^7}, \text{ where } q = 0.0288$$

and the length of mean turn, 40 inches.

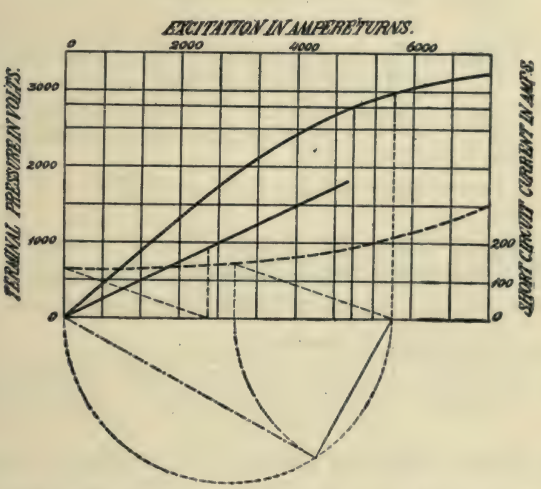


FIG. 86.—CHARACTERISTICS OF 520 KVA., 300 REVS., 60-CYCLE, SINGLE PHASE ALTERNATOR.

368. Particulars of Field Winding.—The sectional area is too small to employ an edge wound, flat strip winding so a No. 6 S.W.G. wire, having a section of 0.02895 square inch, will be used.

With the assumed current density of 1,600 amperes per square inch, the current will equal 1,600 × 0.02895 = 46.5 amperes, and the number of turns per pole will be $\frac{6{,}000}{46.5}$ = 130.

369. Temperature Rise.—The hot resistance of all the coils in series is $\frac{24 \times 130 \times 40}{0.02895} \times \frac{8}{10^7} = 3.45$ ohms; and the maximum value of excitation energy required will be $46.5^2 \times 3.45 = 7{,}400$ watts.

Therefore, the temperature rise will be equal to $T_1 = \frac{100 \times 7{,}400}{8{,}870(1 + 0.0002 \times 6{,}000)} = 38°$ F., as the cooling surface is equal to 8,870 square inches and the mean value of speed, 6,000 feet per minute.

370. Copper Loss in Armature.—The length of mean armature is 77 inches and the resistance of the winding $\frac{48 \times 6 \times 77}{6 \times 0.01629} \times \frac{8}{10^7} = 0.225$ ohms; consequently, the armature copper loss for full load is $186^2 \times 0.225 = 7{,}750$ watts.

371. Iron Loss in Teeth.—The magnetic density in the teeth being 72,500 lines per square inch, the loss per pound of iron will be 5 watts due to hysteresis and 1.26 watts due to eddy currents.

Therefore, the toothed part of the armature, weighing 1,080 pounds, creates a loss of $6.26 \times 1{,}080 = 6{,}750$ watts.

372. Iron Loss in Core.—The weight of the armature core is 4,900 pounds, and the saturation 32,000. Therefore, the iron loss therein will amount to $1.55 \times 4{,}900 = 7{,}600$ watts.

373. Temperature Rise in Armature.—The sum of all the losses in the stationary armature is equal to $7{,}750 + 6{,}750 + 7{,}600 = 22{,}100$ watts, and the radiating surface is 21,250 square inches.

Therefore, the temperature rise will barely exceed $75 \times \frac{22{,}100}{21{,}250} = 78°$ F.

374. Efficiency.—The full load efficiency is equal to $\frac{520{,}000}{557{,}500}$

= 93.4 per cent., after having assumed 8,000 watts for friction and ventilation losses.

375. Summary of Design.—The output constant characterizing the choice of the leading dimensions, will be found equal to $\frac{87.5^2 \times 14.5 \times 300}{520} = 64 \times 10^3$.

The weights of the active and loss producing materials are:

Field copper	1,150	pounds;
armature copper	700	" ;
armature stampings	5,980	" .

This data, compared with that of Figs. 14 and 64, indicates that the present design is, on the average, a standard one.

DESIGN OF AN INDUCTOR TYPE SINGLE PHASE ALTERNATOR.

376. General Specification of Alternator.—The single phase alternator in question is direct coupled to a turbine running at a speed of 1,050 R.P.M.

The generator should be capable of delivering 55 KVA. to a lighting circuit.

A terminal pressure of 2,300 volts is required, with a frequency of 70 per second.

377. Peripheral Speed.—From the following calculations it will be seen that for such a high speed as 1,050 R.P.M., an inductor type machine can be obtained with good electrical features and which at the same time will prove a commercial success.

In this particular type of alternator, having simply a revolving part of iron, the peripheral speed can be driven much higher than in the case of rotating magnet coils.

Assuming a peripheral speed of 6,200 feet per minute, the diameter of the wheel D_1 will be 22.6 inches, where $6{,}200 = \frac{D_1 \times 3.14 \times 1{,}050}{12}$.

Therefore, the value D_1 of 22.6 inches will be used in the design of this particular machine.

378. Arrangement of Field System.—The frequency being 70 cycles per second and the speed 1,050 revolutions per minute, the number of poles will be $2p = \frac{70 \times 60 \times 2}{1{,}050} = 8$.

In this type of alternator, with the armature in two halves, each half will be induced by a magnet wheel consisting of 4 projections, with a pole arc covering the whole pole pitch. Under the influence of the central magnetizing coil, all the projections of one half of the wheel will be of the same polarity, and if the left hand poles are north, the right hand polar projections will have the opposite polarity, namely, south.

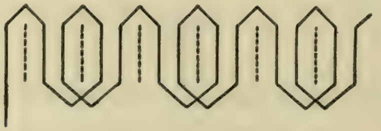


FIG. 87.—WINDING DIAGRAM OF 55 KVA., SINGLE PHASE ALTERNATOR.

The number of closed magnetic circuits in this case is four.

379. Arrangement of Armature System.—For each half of the armature the slots are 24 in number, but only 16 of them will receive the winding and the others are left empty, see Fig. 87.

The pole arc ratio being equal to unity and the coil breadth ratio to $\frac{1}{3}$, the form factor will be 1.6, as the winding employed is of the long coil type.

The two halves of the armature are to be connected in series.

380. Current in Armature.—With reference to Fig. 62, the value of the total flux for this single phase generator is equal to $2p \times F_2 = 12.5 \times 10^6$, or $\frac{12.5 \times 10^6}{4} = 3.1 \times 10^6$ per pole projection, as the ratio KVA. × 1.3 is equal to 0.065.

By means of Equation (**35**), we find the corresponding value of ampere conductors equal to

$$\frac{55}{1,050}=\frac{1.6}{120\times10^{11}}\times12.5\times10^6\ Z\times C, \text{ where } Z\times C=31,500.$$

381. Armature Conductors.—The normal armature current being $\frac{55,000}{2,300} = 24$ amperes, the approximate value of armature conductors will be $\frac{31,500}{24} = 1,310$ total, but we decide on the multiple of the 2×16 slots, which is $16 \times 2 \times 44 = 1,408$.

Therefore, the armature ampere conductors are equal to $1,408 \times 24 = 33,800$; and the peripheral density will be $\frac{33.800}{2 \times 23 \times 3.14} = 237$ ampere conductors per inch.

Each slot will contain 44 conductors, and the value of the ampere conductors per slot will be $24 \times 44 = 1,056$, which is a very reasonable figure.

382. Arrangement of Slots.—The size and form of the slots are 1 inch by 1.75 inches, which provides for 44 No. 11 S.W.G. wires, including 0.1 inch thick micanite slot insulation and an allowance for play as well as for the unevenness of the inner surface of the slot. Fig. 88 shows the general arrangement of the conductors in a slot.

The total sectional area of a conductor will be 0.01057 square inch, which allows a current density of $\frac{24}{0.01057} = 2,270$ amperes per square inch.

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Date

383. Space Factor.—Regarding the space factor, the copper section inside a slot is equal to 44 × 0.01057 = 0.465 square inch, and the sectional area of the slot is 1.75 square inches, which results in a space factor of $\frac{0.465}{1.75} = 0.265$.

384. Value of Useful Flux.—The normal value of useful flux will be found by means of Equation (**33**); $2{,}300 = 1.6 \times 70 \times 44 \times 16 \times 2 \times F_2$ where $F_2 = 1.45 \times 10^6$ lines, providing that the field system is of the alternate pole type, but as the coils leaving a pole enter the air and from there, so to speak, come again under a pole of same polarity, the flux per pole projection in this particular design is equal to $10^6 \times 2 \times 1.45 = 2.9 \times 10^6$ lines.

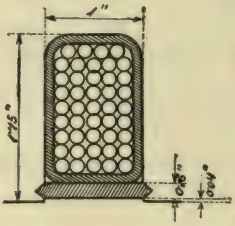

FIG. 88.—SLOT WINDING OF 55 KVA., 1,050 R.P.M., 70-CYCLE, SINGLE PHASE ALTERNATOR.

385. Armature Length.—The iron length of the armature is determined by fixing the permissible saturation of the teeth, with regard to their losses. As the teeth pass through a variable field of 2.9×10^6 to 0 lines of magnetic flux, we will allow a density of 80,000 lines per square inch.

Therefore, the length of the effective iron is equal to

$$\frac{2.9 \times 10^6}{80{,}000} = l \times 2.25 \times 3 = 6.75\ l,$$

where $l = 5.4$ inches per armature half. An additional 0.6 inch must be allowed for the paper insulation between the laminations.

386. Section of Armature Core.—In calculating the armature core section, particular care must be taken that the total height of the armature laminations should not be less than one-half of the pole pitch or pole arc, as with a small height of laminations the variable magnetization would reach the solid iron yoke and produce an excessive iron loss.

In the present case we fix the total height of the laminations in the armature at 5 inches, with a density of

$$\frac{2.9 \times 10^6}{\frac{29.75 \times 3.14}{8} \times 6 \times .9} = 46{,}000 \text{ lines per square inch.}$$

387. Particulars of Yoke.—The sectional area of the armature yoke may be expressed with sufficient accuracy as follows: $\frac{33 \times 3.14}{4} b = 26 \times b = \frac{2.9 \times 10^6}{B_Y}$; and if we allow a density of $B_Y = 46{,}000$ lines per square inch, b, the height of the cast iron yoke, will be equal to $\frac{2.9 \times 10^6}{46{,}000 \times 26}$ $= 2.4$ inches.

The length of the magnetic path in the yoke will be influenced by the space required for the projecting parts of the armature coils and for the central magnetizing coil. An allowance of 6 inches on account of the two armature coil ends and 3 inches for the field coil width, will be a good approximation and, if necessary, it may be altered later.

388. Section of Pole Projection.—When designing the iron wheel it is necessary to assume the value of the leakage factor as a moderate figure. Calculating with $\sigma = 1.10$, the flux passing through a pole projection will be $2.9 \times 1.1 \times 10^6 = 3.2 \times 10^6$ lines. Assuming a density of 75,000 lines per square inch the necessary section is equal to $\frac{3.2 \times 10^6}{75{,}000}$ $= 42.5$ square inches.

With regard to the useful leakage, the length has been fixed at 5.5 inches and the mean width of the pole stamping is equal to $\frac{42.5}{5.5 \times .95} = 8$ inches.

The height of the lamination should not be less than about one-half of the pole arc, otherwise considerable iron losses may take place in the solid part of the pole system.

389. Section of Rim.—In the present case a rim section of about $\frac{10 \times 3.14}{4} \times 6 = 47$ square inches is suitable, which results in a magnetic density of $\frac{3.2 \times 10^6}{47} = 68{,}000$ lines per square inch. The material of the rim is cast steel.

390. Dimensions of Magnetic Circuit.—With reference to the data in the previous paragraphs relating to this particular design, the principal dimensions of the magnetic circuit are indicated in Fig. 89:

Bore of the armature	23	inches
external diameter of the armature lamination	33.0	"
slot width	1	"
slot depth	1.75	"
overall length of the armature half	6	"
overall width of the yoke	21	"
height of the yoke	2.4	"
pole arc	9	"
pole core width (mean value)	8	"
pole core length	5.5	"
pole lamination height	3.5	"
wheel rim overall length	20.5	"
height of wheel rim	6	"

391. The Non-Inductive Load Drop.—The voltage drop on non-inductive load is specified as 6 per cent., and, accordingly, we will assume a ratio of 2.75 between the armature back ampere turns per magnet circuit and the ampere turns of the magnet coil. The choice of this ratio factor allows the armature leakage in this design to be somewhat higher than in the revolving coil type of alternator, and, besides, the value of the short circuit constant will also be higher.

The normal value of the armature back ampere turns is $0.9 \times 16 \times 44 \times 24 = 15{,}200$ total, or, per closed magnetic circuit, $\frac{15{,}200}{4} = 3{,}800$; and that of the field $= 2.75 \times 3{,}800 = 10{,}500$.

If 75 per cent. of the field ampere turns are allowed for the air gaps, the latter will be found from the equation

$$0.75 \times 10{,}500 = \frac{0.313 \times 2\delta}{9 \times 5.5}\, 2.9 \times 10^6, \text{ where } \delta = 0.22.$$

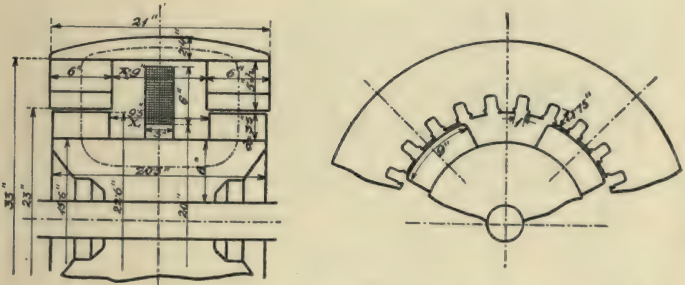

FIG. 89.—DIMENSIONS OF MAGNETIC CIRCUIT OF 55 KVA., 1,050 R.P.M., 70-CYCLE, SINGLE PHASE ALTERNATOR.

For further calculations we take the single air gap equal to 0.2 inches.

392. The Open Circuit Characteristic.—The data for the determination of the open circuit characteristic is tabulated in Table 22. A leakage factor σ of 1.1 has been applied in the calculations, see Par. **388**.

The air gap reluctance is equal to

$$r_0 = \frac{2 \times 0.313}{\frac{9 \times 2 \times 6}{3 \times 0.2} + \frac{6 \times 9 \times (0.2 + 0.5)}{3(0.2 + 0.2)}} = \frac{20.5}{10^4},$$

TABLE 22.

E. M. F.				2 600		2 300		1,800		1,000	
Armature Flux.				3.275×10^6		2.9×10^6		2.27×10^6		1.26×10^6	
Field Flux.				$3\ 6 \times 10^6$		$3\ 2 \times 10^6$		2.5×10^6		1.75×10^6	
Material and Sectional Area of:	Wheel Rim.	Cast Steel. 47	Magnetic Densities and Corresponding Ampere Turns per One Inch Length.	77,000	30	68,000	21	53,000	14	29,500	6
	Pole Core.	0.04″ Sheet 42.5		85,000	40	75 000	28	58,500	16	32,500	6.5
	Teeth.	0.02″ Sheet 36.5		90.000	50	80,000	34	62 500	20	34,750	7
	Armature Core.	0.02″ Sheet 63		52,000	11	46,000	9	36,000	7	20 000	4
	Armature Yoke.	Cast Iron 63		52,000	190	46,000	140	36.000	75	20 000	30
Length of Magnetic Paths.	Wheel Rim.	17	Ampere Turns of the Paths.	510		360		280		100	
	Pole Core.	7		280		195		110		45	
	Teeth	3.5		175		120		70		25	
	Armature Core.	6.5		70		60		45		25	
	Armature Yoke.	15		2,850		2.100		1,130		450	
r_0		29 5 10^4		9,750		8,600		6,750		3,750	
Total Ampere Turns per Pole.				13 635		11,435		8,385		4,395	

and the magnetic resistance of the field leakage path, see Fig. 89, is

$$r_1{}^1=\frac{0.313}{\frac{d\times a}{X_1}+\frac{2d\times f}{X_1+f}+\frac{a+f}{X_1\times f}}=\frac{0.313}{\frac{3.5\times 9}{9.5}+\frac{2\times 3.5\times 5.5}{15}+\frac{9\times 5.5}{15}}=\frac{330}{10^4}.$$

Having ascertained that all previous assumptions are sufficiently correct, especially that of the normal value of field ampere turns, the next step will be the calculation of the short circuit characteristic.

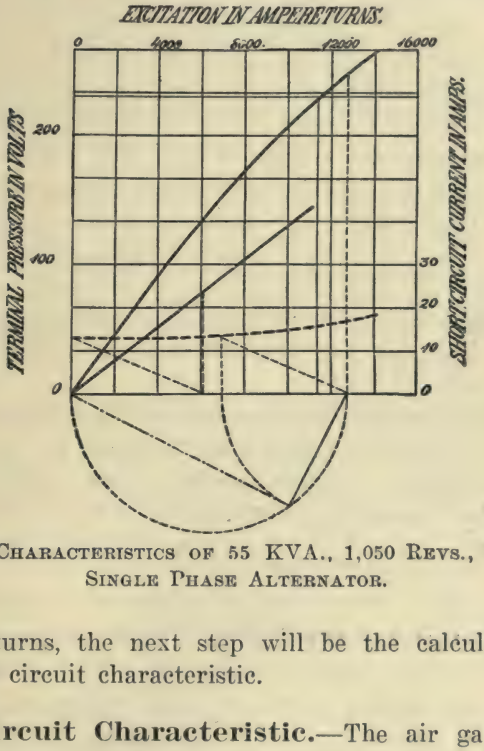

Fig. 90.—Characteristics of 55 KVA., 1,050 Revs., 70-Cycle, Single Phase Alternator.

393. Short Circuit Characteristic.

393. Short Circuit Characteristic.—The air gap reluctance is equal to $\frac{29.5}{10^4}$, and the reluctance of the armature leakage path, see Fig. 89, is

$$r_2{}^1=\frac{0.313}{\frac{4\times i\times l\times o}{s\times\tau}+\frac{4i\times r(\tau+o)}{\tau\times o}+2(\tau+2l_1)+\frac{2\tau h_1}{X_o}+\frac{2\tau\times l\times r}{X_o\times o}}=\frac{40.0}{10^4}.$$

Therefore, the constant of the short circuit characteristic will be $k_s = 1 + \frac{29.5}{49.0} = 1.6$; that is, the normal armature current will be obtained in the short circuited armature, when the field excitation is equal to $1.6 \times 3{,}800 = 6{,}100$ ampere turns.

394. Particulars of Field Coil.—The application of the graphical method shown in Fig. 90 indicates that the specified regulation is complied with.

The maximum excitation required is 13,000 ampere turns, which is supplied by the central field coil.

The terminal voltage of the field coil is fixed at 55 volts, and the approximate length of mean turn is 80 inches; from which the conductor section q, is equal to .0152 square inch, when $55 = 13{,}000 \times \frac{80}{q} \times \frac{8}{10^7}$.

The nearest wire with a section almost equal to .0152 square inch, is a No. 9 S.W.G. with a section of 0.01629 square inch.

When such a deep central coil is used the current density should not exceed 1,000 amperes per square inch, as the cooling conditions are very unfavorable.

The maximum excitation current will be $0.01629 \times 1{,}000 = 16.3$ amperes and the number of turns, $\frac{13{,}000}{16.3} = 800$.

395. Temperature Rise.—The maximum energy utilized in the field winding is equal to $16.3^2 \times 3.15 = 840$ watts and the cooling surface is 1,440 square inches; consequently the temperature rise will be equal to $T_1 = 120 \times \frac{840}{1{,}440} = 70°$ F.

The high factor of 120 has been used in this case because the winding depth and height is comparatively large.

396. Armature Copper Loss.—The armature copper loss amounts to $\frac{16 \times 44 \times 40}{0.01057} \times \frac{8}{10^7} \times 24^2 = 1{,}200$ watts, the normal current being 24 amperes and the length of mean armature turn 40 inches.

397. Armature Iron Losses.—For the calculation of iron losses the method applied in the previous paragraphs, such as **371** and **372**, will give satisfactory results, when allowing for one-half of the hysteresis losses, which would result for a complete change of magnetization and taking the full value of eddy current loss, provided that the total height of armature lamination is about one-half of the pole arc length.

398. Iron Loss in Teeth.—The weight of the armature toothed parts is equal to $2 \times 24 \times 2.25 \times 1.75 \times 6 \times 0.9 \times 0.28 = 280$ pounds. The saturation is 80,000 lines per square inch and the specific losses amount to 5.7 watts. Therefore, the total loss in the teeth is equal to $280 \times 5.7 = 1{,}600$ watts.

399. Iron Loss in Core.—The weight of the laminated armature core is equal to $3.14 \times 29.75 \times 3.25 \times 2 \times 6 \times 0.9 \times .28 = 920$ pounds, and the saturation being 46,000 lines per square inch, the total losses will be equal to $920\,(1.4 + 0.8) = 2{,}020$ watts.

400. Temperature Rise.—The total losses in the armature are, therefore, $1{,}200 + 1{,}600 + 2{,}020 = 4{,}820$ watts, and the cooling surface is composed of the

inner cylinders of.............	880	square	inches
external cylinders of...........	2,200	"	"
and the side faces of...........	1,900	"	"
making a total of..............	4,980	"	"

The temperature rise will be approximately $T_2 = 75 \times \frac{4.820}{4{,}980} = 73°$ F.

401. Efficiency.—The efficiency of the machine under discussion will be $\frac{55.000}{62,420} = 88.3\%$.

The friction and ventilation losses in this case are assumed to be 1,600 watts.

402. Summary of Design.—The resulting good commercial features of the alternator have been obtained with an output coefficient of $\frac{23^2 \times 2 \times 6 \times 1\,050}{55} = 122 \times 10^3$, which, for a high tension and single phase alternator, is a standard value.

The active and loss contributing materials are composed of 1,200 pounds of armature stampings, 95 pounds armature copper, and 330 pounds of field copper, which point to a successful commercial design.

It must be kept in mind that, for low or medium speeds, it is difficult to obtain a good design of inductor type alternator which embodies very good electrical features, complying at the same time with the conditions of economy.

403. Design Sheet.—Table 23 illustrates a typical design sheet, on which all the necessary data required for a given design is collected in a very handy form.

The Table in question gives the data for the calculations of a 175 KVA. alternator.

404. Formulæ Used in Design.—At this stage it will be well to tabulate the various formulæ which are used in the examples of alternator design given above.

Such a list forms a very handy reference, the more so, as it is not absolutely necessary for such formulæ to be committed to memory.

A list of the symbols and specific quantities used in the following formulæ is given at the beginning of this book.

CAPACITY OF THE ALTERNATOR: KVA. $= E \times C$. in the case of single phase open winding; KVA. $= 2E \times C$. in the case

TABLE. 23.:

3 - PHASE GENERATOR.

SHEET NO. 23.	MACHINE NO. 3.	TYPE 35'	DATE.

KW. 150	KVA. 175	VOLTS. 127/220	AMPS. 460	REVS. 400	CYCLES 40	POLES 12	DRAW. NO. 74. 75. 76. 77.

PRIME MOVER: DIRECT COUPLED STEAMENGINE.

HP. 220	REVS. 400	CYCL. VART. —	MOMT. VART. —	FLYWH. EFF. —

ARMATURE		MAGNET WHEEL	
CORE MATERIAL	0·02" SHEET	POLEPIECE MATER.	0·04" SHEET
EXTERN. DIAMETER	49·7	WHEELRIM MATER.	CAST IRON
INTERN. DIAMETER	35·4	EXTERN. DIAMETER	35·1
IRON HEIGHT ABV. SLOT	5	TOTAL POLE HEIGHT	6
SLOT DIMENSIONS	0·8 × 2·15	POLE ARC	6
NO. & SIZE OF VENT. DUCTS	2 — ½	POLE WIDTH / LENGTH	3·75 × 12
IRON LENGTH	12	RIM HEIGHT / LENGTH	3 × 18
OVERALL DIAMETER	—	SHAFT IN WHEEL	—
OVERALL LENGTH	—	BEARINGS DISTANCE	—
NO. OF PHASES	3	NO. OF POLES	12
CONNECT. OF PHASES	STAR	KIND OF WINDING	MACHINE WOUND
KIND OF WINDING	FORMER WOUND	TURNS PER POLE	110
NO. OF SLOTS	36	WIRES IN PARALL.	—
NO. OF SLOTS P. POLE	3	SIZE OF WIRE	6 SWG.
NO. OF CONDT. P. SLOT	3	NORM. AMP. TURNS P. POLE	4000
NO. OF WIRES P. COND.	8	CURRENT DENSITY (MAX)	1700
SIZE OF WIRE	6 SWG.	TOTAL RESIST. OF COILS	1·32
NO. OF COND. P. PHASE	36	NO. OF BRUSHES	2 per ring
AMP. COND. P. INCH PERI.	447	AIRGAP	0·15
CURRENT DENSITY	1980	POLEPITCH	9·18
RESIST. P. PHASE	0·0035	LEAKAGE FACTOR	1·25
FORMFACTOR	2·46	TOT. USEFUL FLUX	43·2 × 10⁶
INSULATION IN SLOT	0·045	SIZE OF BRUSHES	For 50 AMPS.

		NO LOAD	FULL LOAD cosφ·1	FULL LOAD cosφ·85		
MAGNET. DENSIT.	ARMAT. YOKE	—	—	—	—	SECTION. AREA.
	ARMAT. CORE	35300	36700	39500	51	
	ARMAT. TEETH	73500	76500	82500	49	
	POLE CORE	106000	110000	119000	43·2	
	WHEEL RIM	42500	44100	47600	54	
	AIR RELUCT.	8/10⁴	8/10⁴	8/10⁴	—	
AMP. TURNS P. POLE	ARM. YOKE	—	—	—	—	LENGTH OF PATH
	ARM. CORE	45	45	50	7	
	ARM. TEETH	55	60	80	2·15	
	POLE CORE	675	980	1525	5	
	WHEEL RIM	350	400	465	3·2	
TOT. AMPT. P. POLE		4000	4460	5350		

WEIGHT OF	ARM. YOKE	—	WEIGHT OF	POLE PIECE	950	ARMAT.	9050	COOLING SURF.
	ARM. CORE	2900		FIELD COPPER	440			
	ARM. TEETH	580		WHEEL RIM	950			
	ARM. COPPER.	225		ARMS	—	FIELD	3660	
	TOT. STATOR	—		TOTAL WHEEL	—			
LOSSES IN	ARM. CORE	4150	LOSSES IN	FIELD COPPER	3180	ARM.	72°F.	TEMP. RISE
	ARM. TEETH	2370		BEARG. FRICT.	—			
	ARM. COPPER	2200		AIR FRICTION	—	FIELD	65°F.	
TOTAL LOSS IN ARM		8720	TOTAL LOSS IN WHEEL		6980			

LOAD	EFFIC.	VOLT DR.	EXCIT. TYPE	—	FIELD RHEOST. TYPE	—
FULL cosφ.85	92%	12·2%	EXCIT. OUTPUT	3·75	RESIST. IN RHEOS.	—
½ FULL	87%	—	MAX. EXC. VOLTS	65	NO. OF CONTACTS	—
FULL cosφ.1	—	4%	MAX. EXC. AMPS.	49	MIN. EXC. AMPS.	36

REMARKS: SUITABLE STAMPINGS IN STOCK, STANDARD SHELL TO BE USED.

REMARKS

SPECIFIED CONDITIONS:

FULL LOAD cos ψ = 0·85 EFFIC. 91%
½ LOAD " " " 87%

VOLTAGE DROP ON
FULL INDUCT. LOAD cos ψ = 0·85 12%
" NONIND. " " = 1 4%

TEMPERATURE RISE 75°F.

of two phase two open windings; KVA. $= 3E \times C.$ in the case of three phase, star winding.

NUMBER OF POLES: $\dfrac{120 \times n}{N} = 2p.$

PERIPHERAL SPEED: $V = \dfrac{D_1 \times \pi \times N}{12}.$

POLE PITCH: $\tau = \dfrac{D_1 \times \pi}{2p}.$

POLE ARC RATIO: $\dfrac{a}{\dfrac{D_1 \times \pi}{2p}}.$

SLOT PITCH: $o = \dfrac{D \times \pi}{S}.$

NUMBER OF SLOTS PER POLE AND PHASE: $\dfrac{S}{m \times 2p}.$

SLOT CAPACITY: $\dfrac{m \times Z \times C}{S}.$

NUMBER OF ARMATURE AMPERE CONDUCTORS: $m \times Z \times C.$

PERIPHERAL DENSITY: $\dfrac{m \times Z \times C}{D \times \pi}.$

THE FUNDAMENTAL EQUATION OF USEFUL FLUX: $10^8 \times E = Const. \times n \times Z \times F_2.$

THE EFFECTIVE TEETH SECTION: $\dfrac{F_2}{B_t} = \dfrac{a}{o} r \times l \times 0.9.$

THE OUTPUT COEFFICIENT: $\dfrac{D^2 \times l \times N}{KVA.}.$

THE ARMATURE CORE SECTION: $\dfrac{F_2}{2B_a} = k \times l \times 0.9.$

THE FIELD FLUX: $F_1 = \sigma \times F_2.$

THE POLE CORE SECTION: $\dfrac{F_1}{B_p} = b \times f \times 0.95.$

THE WHEEL RIM SECTION: $\dfrac{F_1}{2B_r} = g \times h.$

THE GAP RELUCTANCE: $r_0 = \dfrac{0.313}{\dfrac{a \times r \times l}{o \times \delta} + \dfrac{l \times a \times \left(u + \dfrac{s}{2}\right)}{o(u + \delta)}}.$

THE RELUCTANCE OF FIELD LEAKAGE PATH:

$$r_1^1 = \frac{0.313}{\frac{4c \times f}{n} + \frac{4d \times f}{m} + \frac{4b \times d}{m+b}}.$$

THE RELUCTANCE OF ARMATURE LEAKAGE PATH:

$$r_2^1 = \frac{0.313}{\frac{4i \times l \times o}{s \times \tau} + \frac{4i \times r(\tau + o)}{\tau \times o} + \tau + 2l_1}.$$

THE LEAKAGE FACTOR: $\sigma = 1 + \frac{r_0}{r_1^1}$.

THE SHORT CIRCUIT CONSTANT: $k_s = 1 + \frac{r_0}{r_2^1}$.

THE ARMATURE BACK AMPERE TURNS: $A_2 = 0.9 \times Z \times C$. in single phase alternators; $A_2 = 1.41 \times Z \times C$. in two phase alternators; $A_2 = 2.12 \times Z \times C$. in three phase alternators.

THE EQUIVALENT FIELD AMPERE TURNS: $A_{1s} = k_s \times A_2$.

THE FUNDAMENTAL EQUATION OF FIELD WINDING:

$$e = \frac{z \times C_1 \times 2p \times L_1}{q_1} \times \frac{8}{10^7}.$$

THE EXCITATION ENERGY: $e \times C_1 = W_m$.

THE COOLING SURFACE OF FIELD COILS: $O_1 = L_1 \times d \times 2p + 2b \times f \times 2p$.

THE TEMPERATURE RISE OF ROTATING FIELD COILS: $T_1 = Const. \times \frac{W_m}{0_1 (1 + 0.0002 \times V)}$.

THE RESISTANCE OF ARMATURE PHASE WINDING: $\frac{Z \times L_2}{q_2} \times \frac{8}{10^7}$.

THE ENERGY CONSUMPTION IN ARMATURE WINDING: $m \times C^2 \times \frac{Z \times L_2}{q_2} \frac{8}{10^7} = W_a$.

THE HYSTERESIS AND EDDY CURRENT LOSSES IN TEETH:

$$S \times i \times r \times l \times 0.9 \times 0.28\,(w_h + w_e) = W_t$$

THE HYSTERESIS AND EDDY CURRENT LOSSES IN ARMATURE CORE:

$$(D_2 - k)\,\pi \times k \times l \times 0.9 \times 0.28\,(w_h + w_e) = W_c$$

THE COOLING SURFACE OF ARMATURE:

$$D_2 \times \pi \times l + D \times \pi \times l + \frac{D_2^2 - D^2}{4}\pi(2 + 2\lambda) = O_2.$$

THE TEMPERATURE RISE ON STATIONARY ARMATURE:

$$T_2 = 75\,\frac{W_a + W_i}{O_2}.$$

THE EFFICIENCY OF THE ALTERNATOR:

$$\eta = \frac{KVA}{KVA + W_a + W_i + W_m + W_f}.$$

PRACTICAL WORKING OF ALTERNATORS.

405. Paralleling.—In Book **37**, pages 17 to 37, the subject of paralleling is fully dealt with, but the following remarks will be of interest, as they concern the design of the generators.

406. Rise in Terminal Voltage.—If an alternator is switched on a line possessing considerable condenser effect, the terminal voltage will rise considerably, due to the combined effects of the inductance of the generator armature and of the capacity of the line.

In some cases the voltage will rise to such a value that it becomes disastrous to the machine as well as to the line.

This effect generally happens with alternators which have a wave form differing from the sinusoidal form, as the harmonics of the higher periodicity come into play.

With the view of a possible voltage rise, it is necessary to design the insulation with an ample factor of safety, or if such voltage rise is anticipated and its prevention is necessary, it is found desirable to design the alternator with a large number of slots, as well as with rounded and shaped poles, so as to approach the sinusoidal wave form as closely as possible.

407. Causes of Cross Currents.—With regard to the parallel running of alternators, the designer should remember the following points:

Alternators which have to work in parallel, must have similar wave forms in order that no cross current shall appear in the armatures, and here again the most favorable conditions are offered by a sinusoidal wave form.

Two or more alternators running in parallel have a certain control over each other, and if there is a difference in their speed, then one transfers load to the other, which reveals itself by a cross current between the armatures. This control or synchronizing power is larger, the smaller the reactance of the armature, that is, the better the regulation.

Alternators with low voltage drop are liable to heavy cross currents if the machines are accidentally thrown out of step.

408. Speed Variation.—There is little trouble with alternators driven by water wheels or steam turbines, owing to their uniform rotation.

In the case of reciprocating steam engines as prime movers, a good engine governor is a most important thing, and every precaution should be exercised in order that the angular variation of the speed shall be kept within small limits.

Such a condition must receive the close attention of the designer, especially if a low voltage drop is specified.

409. Flywheel Effect.—To keep the angular variation within small limits it is necessary to apply a certain amount of flywheel effect and it is the best practice to put as much of the rotating mass in the alternator as possible.

Very often the designer is compelled to increase the diameter of the magnet wheel in order to find room for the revolving mass, which necessitates a sacrifice in the electrical properties of the alternator.

410. Speed and Flywheel Effect.—The amount of the necessary flywheel effect is usually specified by the engine maker and the alternator designer has to dispose his material accordingly.

For medium and high speed alternators it is not difficult to comply with the specification of the engine maker, but for low speed generators the placing of the rotating weight inside the magnet wheel becomes a vital question, which needs very careful consideration.

411. Values of Flywheel Effects.—It is a general practice to express the flywheel effect by the product of the revolving weight in tons, multiplied by the square of the gyration diameter in feet.

TABLE 24.

KVA		200		300		500		800	
Flywheel Effect in Ton Feet Square.		Normal.	Maximum.	Normal.	Maximum.	Normal.	Maximum.	Normal.	Maximum.
Speed in Revolutions per Minute.	200	110	200	165	295	235	370	410	620
	150	235	460	280	510	600	1,000	800	1,200
	125	300	620	680	1,000	1,100	2 150	1.450	2,450
	107	750	1,600	1,200	2 800	1,750	3,800	2,200	4,200
	94	1,100	2,400	1,800	4,200	2,800	6 500	3,500	7,400

Table 24 indicates for low speed alternators the usual values of flywheel effects, as well as the maximum values, which may be placed in the magnet wheel of alternators of various sizes and speeds.

412. Paralleling and Direct Coupled Sets.—The direct coupling of prime mover and generator gives the most compact arrangement and a good efficiency. It is found advisable to place as much flywheel effect in the alternator as possible, or, if it is placed outside it should be close to the magnet wheel, which tends to prevent vibration of the shaft. It should be noted that the application of solid poles or special damping arrangements, such as brass bridges between the poles, will considerably assist the even parallel running of alternators.

413. Necessity of Balancing Alternators at Work and Causes of Failures.—With modern alternators of the rotating field and stationary armature type, there is very little trouble connected with their general working, provided that the paralleling question is satisfactorily solved.

From a mechanical point of view, it is necessary that the magnet wheel should be properly balanced and centred inside the armature bore, otherwise a one-sided pull will appear, as well as unsymmetry in the magnetic fields and, consequently, in the armature E.M.F., which is especially troublesome in the case of a closed winding, for instance, with a mesh connected, three phase machine, where surging currents are likely to appear.

414. Heating and Humming.—Single phase generators with solid poles often run cool on a non-inductive load, but run hot if the armature carries a lagging current, and if wide, open slots are used, a humming noise is produced. In both cases the proper rounding of the pole shoes, closing of the slots, application of many slots and use of a large air gap, will in all probability remedy the above defects.

415. Faults in the Windings.—The most delicate parts of an alternator are, of course, the armature and magnet windings, but only gross carelessness and inattention will cause a breakdown of same. The principal reasons of failure are rupture or disconnection of the winding, faulty insulation between the turns of a coil or between the coils themselves, which short circuits the copper, and faulty insulation of the windings to the iron, or earth.

416. Terminals and Slip Rings.—If the necessary care is taken, there will be very little trouble with the terminals, and up to about 1,000 volts, marble terminal boards will be found satisfactory, while for higher voltages insulators of proper form and arrangement should be used.

The slip rings seldom cause any trouble, but it is advisable to employ at least two sets of brushes of ample section, so that if one goes wrong the other should be able to carry the full current.

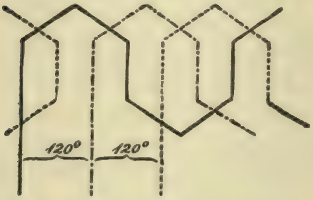

FIG. 91.—THREE-PHASE ARMATURE WINDING PROPERLY CONNECTED.

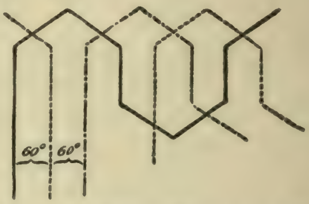

FIG. 92.—THREE-PHASE ARMATURE WINDING WRONGLY CONNECTED.

417. Field Coils.—It should be noted that the field coils sometimes heat up; this is due in most cases to too much taping and wrapping.

If the field coils project out of the pole shoe strong end plates should be used in order to prevent the coils bending upward on account of the centrifugal forces.

418. Connection of Three Phase Armature.—In connecting the different phase windings of a three phase alternator, it is necessary to see that the coils are properly joined up at their ends, which should be 120 degrees apart in the pole pitch, as an armature with the coils connected 60 degrees apart will not generate the full voltage, see Figs. 91 and 92.

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DESIGN OF ALTERNATING GENERATORS AND SYNCHRONOUS MOTORS.

DESIGN OF SYNCHRONOUS MOTORS.

419. The Principle of the Synchronous Motor.—A synchronous motor is simply a reversed alternator and most manufacturing firms use their generator designs without any alteration, for synchronous motors. If a machine, instead of being driven by a prime-mover and generating a current at a certain voltage, is fed by a current at the same terminal pressure, it will be capable of developing mechanical energy approximately equal to $KW \times 0.746$ horsepower, when running at a synchronous speed which may be determined by Equation (**7**).

420. Two Principal Features will be noted in the working of *synchronous* motors : The synchronous motor does *not* start up by itself when the armature is switched on to the supply circuit, the field at the same time being fully excited, but the armature must be run up to the synchronous speed, (see Par. **427**) before it can exert its power. The characteristic working condition of this type of motor is, that the speed is strictly constant according to the frequency and number of poles.

421. Starting of Synchronous Motors.—The method of starting and switching a synchronous motor into circuit is as follows : The motor being at rest, the main switch S_1, Fig. 93, as well as that of the excitation circuit S_2 is kept open and all the resistance of the rheostat R_1 is inserted. The armature is then run up (see Pars. **427** and **428**) to its normal or synchronous speed, and the machine excited as follows:

1. Close the switch S_2.

2. Regulate the excitation by means of the rheostat R_1, till the voltmeter, V_2, indicates the same volts as the voltmeter V_1; that is, the voltage on the motor armature should be the same as that on the line.

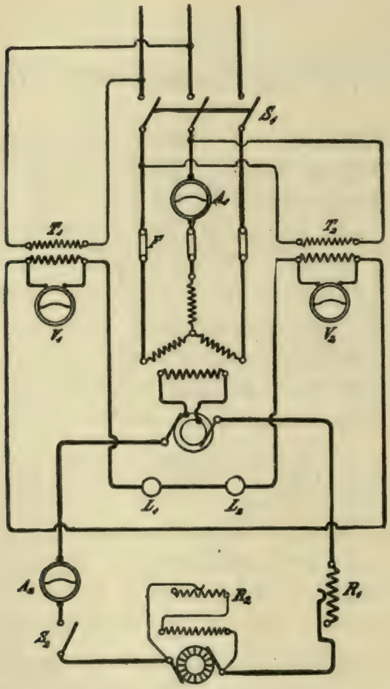

Fig. 93.—Connection Diagram for Synchronous Motor.

3. Connect the motor armature to the line as follows: First close the circuit of the two lamps L_1 and L_2 which constitute the synchronizing device, and regulate the speed of the motor, if necessary, until the pulsations of the lamps become longer and longer; then close the switch

S_1, at the moment both lamps show their *maximum* brilliancy.

4. After the switch S_1 is closed, the load may be *gradually* put on the motor and when the average load is obtained, the excitation should be so regulated, that the armature current becomes a *minimum*, which can be observed on the ammeter A_2.

422. Stopping of Synchronous Motors.—The stopping of the motor involves the following operations:

1. Gradual taking off of the load.
2. Regulating the excitation to its minimum.
3. Quick opening of the main switch S_1.
4. Inserting of all the resistance in the rheostat R_1.
5. Slow interruption of the excitation circuit by means of the switch S_2.

423. Characteristics.—A synchronous motor can be adjusted to have a power factor equal to unity, that is, to bring the terminal pressure and the armature current in phase. This condition will be obtained for a certain excitation and if the field is *under* excited, the armature will carry a *lagging* current; or if the excitation is *higher* than that corresponding to a power factor of unity, the armature will carry a *leading* current.

This feature of the synchronous motor is a most valuable one, as it can be used for improving the power factor of the line, the leading current having the same effect as a condenser in the circuit.

424. Desirable Features.—It is desirable, that with slight changes in the excitation, noticeable pressure alterations should take place; therefore, as will be seen later, it is an advantage to work on the part *below* the knee or bend of the no-load characteristic curve.

425. Speed.—The speed of a synchronous motor is absolutely constant if the prime mover of the supply generator maintains a constant speed, but any irregularity in the generating station, transmission line or distribution system, will be felt by the motor. If the speed variations are not within the standard values, then *hunting* of the synchronous motors will be set up, that is, the speed will vary within larger or smaller limits, decreasing and increasing at intervals.

If the motor is fed by slow speed generators, the field system should have either solid poles or laminated poles with suitable damping arrangements and, as a general designing rule when damping arrangements are used, it may be stated, that the rotating weight of the synchronous motor should be comparatively *small*, so as to permit the taking up of the changes in frequency.

426. Overload Capacity.—The *momentary* overload capacity of synchronous motors, that is, the greatest output before falling out of step, is generally large; standard generators used as synchronous motors will stand a momentary load of about double, and more, of the normal output.

A generator of *small voltage drop*, will correspond to a synchronous motor of *large overload capacity,* and vice versa.

427. Methods of Starting.—The greatest disadvantage of a synchronous motor is, that it must be *brought up* to its *synchronous speed* before it can give the required power, see Par. **420.**

This class of motor is generally used in large sizes, in connection with continuous current dynamos in substations, or for heavy mill work. When starting up on a light load, the exciter may be utilized or an auxiliary starting motor used, whichever way may be found the most convenient. A line of shafting already running also provides a convenient method of starting up.

428. Self Starting Motors.—Synchronous motors are not usually made self starting, but in cases where a self starting motor is required, such a condition can be carried out by applying solid poles or heavy dampers, which will act in a similar manner to that of the rotor of an induction motor when the stator circuit at the supply mains is closed.

The starting torque obtained in such a self starting device of a polyphase synchronous motor, is less than 25% of the normal, thus producing a heavy rush of current.

Another matter to be considered is, that through a transformer action, excessive voltage will be induced in the field coils, especially if they are wound for high excitation voltage with a large number of turns. The high voltage induced in the field coils is likely to cause breakdowns and accidents, but this rise may be diminished by short circuiting the field coils, or by grouping them in parallel during the operation of starting.

429. Data Required by the Designer.—A motor is intended to develop a certain mechanical energy expressed in horse power, when running at a certain speed of N revs. per minute and fed by a current of N cycles under a pressure of E volts. Further, there are specified or assumed, as the case may be, the values of the efficiency and overload capacity.

The design of a synchronous motor and its calculation is identical with that of a generator; by converting the mechanical output in H.P. into the electrical input expressed in KVA., one can follow up the method developed in the previous examples.

430. Example 27.—Method of converting the mechanical output into electrical energy and calculation of the input:

A three phase synchronous motor has to be capable of developing a normal power of 450 H.P. when running at a speed of 500 revs. per minute, the machine being fed by a current at 50 cycles under a terminal pressure of 3500 volts. Further, it is specified that for the normal working, the armature should carry a leading current with a power factor, $\cos \varphi = 0.9$, whereby the efficiency shall not be less than 94%.

SOLUTION: The normal mechanical *output* being equal to 450 H. P. its equivalent in K.W. will be $K.W. = H.P. \times .746 = 335\ K.\ W.$; and under the specified conditions the *input* amounts to $\dfrac{K.W.}{\cos\varphi \times \eta} = \dfrac{335}{0.9 \times .94} = 400$ KVA.

Therefore for a *star* connected armature, the *phase* current will be $\dfrac{400{,}000}{1.73 \times 3500} = 66$ amps. See Equation (**5**).

431. Data for Design.—In comparing the present data with that of Par. **210**, it is obvious that the alternator design developed in Pars. **211** to **268** may be used for this particular synchronous motor.

432. Interpretation of Characteristics.—Fig. 94, contains five different characteristics: The curves 1, 2 and 3 are the no-load, short circuit, and load characteristics, respectively, the latter referring to an armature phase current of 66 amps. with a phase displacement of $\cos\varphi = 0.9$.

Curve No. 4, is the so called V-characteristic of a synchronous motor and gives the armature current in terms of the excitation when the mechanical output 450 H.P., the terminal pressure 3,500 volts, and the speed 500 revs. per minute, are constant. See Par. **440**.

Curve No. 5, represents the corresponding power factors in terms of the excitation.

433. Important Characteristics.—All the working conditions of the machine as a generator or motor, are entirely fixed by the no-load and the short circuit characteristics and the three other curves are simply deduced from these, to illustrate the various electrical features.

The no-load and short circuit characteristics permit further conclusions with regard to the mechanical property of overload capacity.

434. Overload Capacity.—In the following paragraphs the overload capacity is understood to be the ratio between the *maximum* mechanical output and the *normal* output, the former being the greatest energy which can be developed by the motor with a normally excited field before it falls out of step.

Within the practical limits of excitation the overload capacity increases with the exciting current, but this feature is not important.

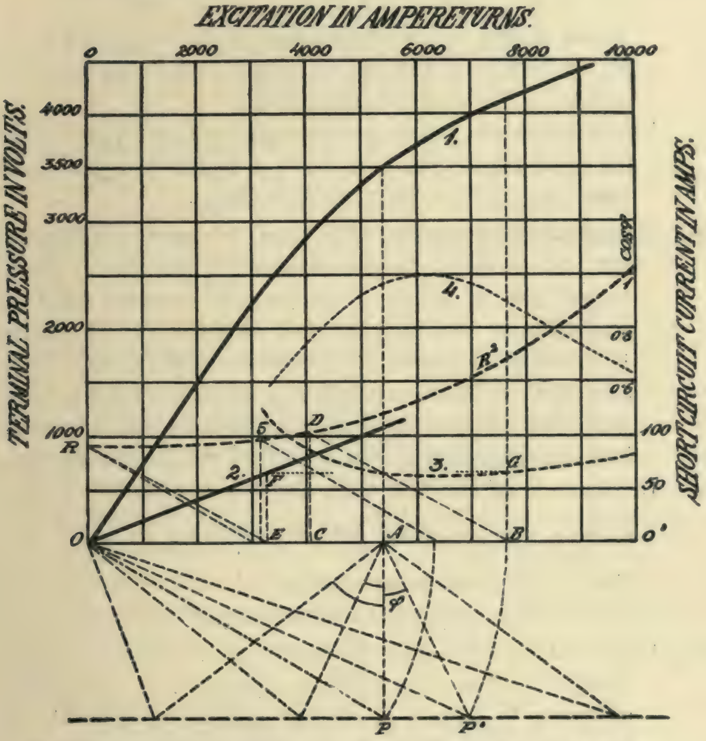

FIG. 94.—CHARACTERISTICS OF 450 H. P., 500 REVS., 50-CYCLE SYNCHRONOUS 3-PHASE MOTOR.

435. Practical Ratio.—The designer considers it sufficient to know, that there is an ample margin of overload capacity, which is directly indicated by the ratio between the *short circuit* current, which corresponds to the normal excitation, and the *normal armature* current.

In standard alternator designs, the above ratio is about 2 or more; that is, with the normal excitation, the machine can stand a momentary overload which is about double the rated capacity.

436. Maximum Load Rule.—In the design, it will be sufficient to work with the approximate rule, that the *maximum* load with normal excitation is equal to

$$K.W._{m} = m \times E_{p} \times C_{s} \quad - \; - \; - \; - \quad (42)$$

where $K.W._{m}$ is the maximum power expressed in K.W.; E_{p} the terminal pressure per phase; and C_{s} the short circuit current with normal excitation.

From the above rule it follows, that an alternator designed for good regulation, will have a larger overload capacity than one with a large voltage drop.

437. Small Overloads.—In cases where sudden overloads are not possible, as for instance when the synchronous motor has to drive a continuous current dynamo for accumulator charging, it will be sufficient to design for 1.25 overload capacity. Consequently, in such cases, the armature will receive a great number of ampere turns, while the value of the field ampere turns remains standard, but at the same time the iron part will be greatly reduced.

In the case of the 450 H.P. three phase motor under discussion, the overload capacity is equal to $\frac{137.5}{59.5} = 2.3$; that is, the maximum mechanical load with 6,300 ampere turns excitation will be equal to $2.3 \times 450 = 1035$ H.P.

438. The V Curve.—The **V** curve of a synchronous motor, indicates what alteration is necessary in the excitation, in order to obtain a current supply with power factor $\cos \varphi = 1$ or $\cos \varphi = < 1$, either with lagging or leading displacement.

With regard to steady running, as well as a safeguard in case of false regulation, it is desirable that the alteration in the phase angle should result in a wide range of the excitation regulation; that is, the armature reactance and also the voltage drop should not be chosen too small.

439. Flat V Curve.—From the above it follows that the flatter the **V** characteristic curve, the steadier will be the running of the motor. This condition tends to cheapen the design, as the number of armature ampere turns may be higher or the number of field ampere turns less. In the case of a large armature reactance, it is not desirable to drive the saturation in the iron parts too high, otherwise the range of regulation will become too excessive in order to obtain a certain amount of phase displacement.

In the case of a large armature reactance, it is well to take the pole arc ratio somewhat smaller than usual, to keep the saturation in the pole and rim at moderate values and to make the air gap larger so that the latter will utilize the principal part of the necessary ampere turns.

The saturation of the teeth and armature core is determined by the specified efficiency.

440. Determination of V Curve.—In order to determine the **V** curve of the synchronous motor the no-load and short circuit characteristics of the machine, when it is driven at normal synchronous speed as a generator, should be known.

As already mentioned, the **V** characteristic gives the armature current in terms of the excitation, for a constant speed, terminal voltage and mechanical load. These conditions of constancy imply, that the watt component of the armature current, $C_1 \cos \varphi$ must also be a constant value, because the mechanical output is proportional to the input in K.W., which is expressed by K.W. $= m \times E_1 \times (C_1 \cos \varphi)$.

441. Ampere and Excitation Values.—The constancy of the voltage, load and watt component of the armature current, is represented in Fig. 94, by the line PP^1 which is parallel to the line OO^1. In Fig. 94, the ampere values as well as the terminal voltage are substituted by the corresponding ampere turns.

The length OA (ampere turns) indicates the constant terminal pressure of 3500 volts, the length AP (ampere turns) corresponds to the armature current, of which the minimum value is the watt component, represented by the line AP, while the length OP is the excitation value.

442. Other Points on Curve.—With the simple determination of the regulation, say, for an armature current corresponding to the normal load, to a normal voltage and to $\cos\varphi=1$, we have fixed one point of the line PP^1 as well as one point of the **V** characteristic and, therefore, it is a simple matter to find other points.

The various values of the lines AP and AP^1 can be easily converted into amperes by means of Equations **(30)** to **(32)**.

443. Actual Results Obtained.—In Fig. 94, the graphical method is developed for the 450 H.P., 3500-volt star connected armature, where the normal watt components will have the value of $C_1 \cos\varphi=\frac{450\times746}{1.73\times3500\times.94}=59.5$ amperes, the efficiency being equal to 94 % and the corresponding field excitation 6300 ampere turns, as found by the graphical determination of the regulation. The current value of the 59.5 amperes, plotted above 6300 ampere turns, gives one point of the **V** characteristic.

444. Determination of Other Points.—Further points on the **V** curve may be found in the following manner: Having obtained a point P, by applying the graphical method of determining the regulation, one has simply to draw a line through this point P parallel to the abscissa line OO^1 and erect another triangle on the line OA so that the point P^1 falls on the parallel line. The length OP^1 will now represent the value of the field excitation, and the line AP^1 indicates the ampere turns which correspond to the armature current on short circuit.

445. Results of Complete Graphical Method.—Make $OP^1=OB$, the length $BC=AP^1$ and draw the perpendicular CD until it cuts the R^2 curve at D. Mark the line DB and draw a parallel to it, the line ER, through the point R;

the short circuit current EF corresponding to OE, will be the ordinate of the **V** curve when BG, erected perpendicular to OO^1, through the point B, is made equal to EF. This method is applied in Fig. 94 for the under and over excited states of the synchronous motor.

446. Resultant Shape of Curve.—The same method may be applied for any other load of the motor and it should be noted that the smaller the load, the steeper will be the branches of the **V** curve.

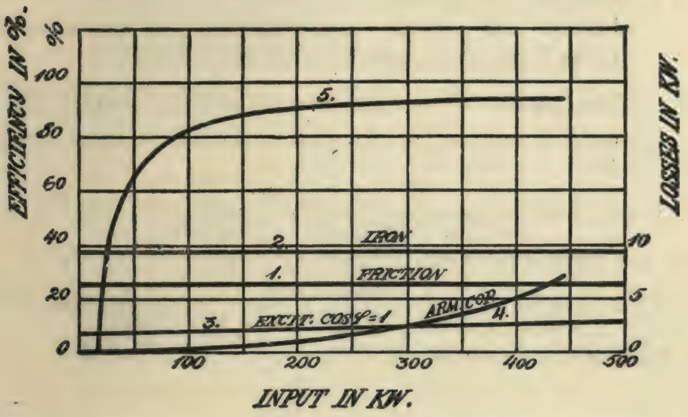

FIG. 95.—EFFICIENCY CURVES OF 450 *H. P.*, 500 REVS., 50-CYCLE SYNCHRONOUS 3-PHASE MOTOR.

447. Power Factor Curve.—The corresponding power factor curve is obtained simply by plotting the values of cos φ in terms of the respective ampere turns. The respective angles φ are indicated in Fig. 94.

For the particular case of the 450 H.P. motor, the V and power factor curves indicate that the field excitation is to be increased from 6,300 ampere turns to 7,600 per pole, if the armature has to carry a leading current of cos $\varphi = 0.9$ phase displacement.

448. Other Characteristics.—A second group of characteristics is given in Fig. 95.

Curve No. 1, represents the friction and ventilation losses in terms of the input expressed in K.W.; curve No. 2, is that of the iron losses; curve No 3, gives the field copper losses; curve No. 4, gives the armature copper losses; and curve No. 5, indicates the efficiency of the machine at different values of input, when the phase displacement is assumed equal to cos $\varphi = 1$.

It should be noted that the efficiency curve starts at an abscissa of 17.5 K.W. which represents the no-load losses, composed of the friction, iron and the minimum excitation losses. The energy consumption in the armature copper at no-load is insignificant and negligible.

449. Efficiency.—The efficiency is the ratio between the useful output and the useful output *plus* all the losses expressed by

$$\eta = \frac{\text{H.P.} \times 746}{\text{H.P.} \times 746 + W_a + W_i + W_m + W_f} \quad \ldots \textbf{(43.)}$$

and in the present case the full load efficiency is equal to

$$\eta = \frac{450 \times 746}{450 \times 746 + 3{,}900 + 9{,}400 + 2{,}700 + 6{,}500} = 94\%$$

with a power factor cos $\varphi = 1$.

DESIGN OF A REVOLVING FIELD TYPE THREE PHASE SYNCHRONOUS MOTOR.

450. General Specification.—A three phase synchronous motor of the revolving field type is to be designed with a star connected armature for a terminal pressure of 3,460 volts and a speed of 375 revs. per minute, when supplied with a current at 50 cycles.

The normal mechanical capacity of the motor is 550 H.P., but the machine should be capable of carrying a wattless leading current, so that a power factor of cos $\varphi = 0.9$ is obtained.

The temperature rise should not exceed 75 degrees Fahrenheit on any part of the motor, and the full load efficiency with a power factor $\cos \varphi = 0.9$ should not be less than 94%.

451. Input.—The electrical equivalent of the mechanical output is equal to $550 \times .746 = 410$ K.W. With an efficiency of $\eta = 0.94$, the electrical input will be $\frac{410}{0.94} = 435$ KVA. with a power factor, $\cos \varphi = 1$; and $\frac{410}{0.94 \times 0.9} = 485$ KVA. with a power factor, $\cos \varphi = 0.9$.

452. Phase Current.—From Equation (**5**) the armature phase current is equal to $\frac{485{,}000}{1.73 \times 3{,}460} = 81$ amperes, with $\cos \varphi = 0.9$, and $\frac{435{,}000}{1.73 \times 3{,}460} = 72.5$ amperes with $\cos \varphi = 1$.

453. Total Flux.—The total amount of useful magnetic flux will be found by means of the ratio, $\frac{\text{KVA.}}{N} = \frac{485}{375} = 1.29$ and Fig. 62, where $2p \times F_2 = 67.5 \times 10^6$. Or, as the number of poles is equal to $2p = \frac{120 \times 50}{375} = 16$, see Equation (**7**), the useful flux per pole will be about $\frac{67.5 \times 10}{16} = 4.25 \times 10^6$ lines.

454. Armature Winding.—The armature winding will be of the former wound *long coil* type, placed in *open* slots. Assuming a total number of slots $S = 96$, that is, 2 per pole and phase, with a pole arc ratio of 0.65, found by means of Table **14**, the form factor will be found equal to 2.3.

455. Armature Conductors.—By the application of the Equation (**35**), the number of armature ampere conductors is equal to $\frac{485}{375} = (3Z \times C_2) \times 67.5 \times 10^6 \frac{2.3}{120 \times 10^{11}}$, where

$3Z \times C_2 = 100{,}000$; and the phase current being 81 amperes, the number of total armature conductors will be $\frac{100{,}000}{81} = 1240$, or the nearest multiple of the slot number, $96 \times 13 = 1248$, which gives 13 conductors per slot.

456. Size of Conductors.—With 13 conductors per slot and 81 amperes per phase, the slot capacity will have the standard value of $13 \times 81 = 1{,}053$ ampere conductors; and allowing a current density of 2,000 amps. per square inch, the application of 2 parallel connected No. 8, S.W.G. wires per conductor, results in a favorable slot shape.

457. Dimensions of Slots.—The slot dimensions Fig. 96 are equal to $s = 0.75$ inches in width and $i = 2.1$ inches in depth,

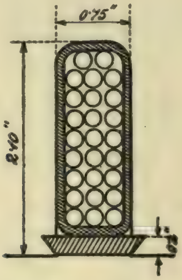

Fig. 96.—Slot Winding of 550 h. p., 3460 Volt, Synchronous 3-Phase Motor.

which provides amply for the total number of 26 wires with double cotton covering, for the 0.08 inch thick micanite insulation, and for the unevenness of the assembled stampings, and also a fixing wedge 0.2 inch in thickness.

458. Diameter of Magnet Wheel.—The total value of armature ampere conductors being $1248 \times 81 = 101{,}000$ with a peripheral density of 500 ampere conductors per inch, the armature diameter is equal to $\frac{101{,}000}{500 \times 3.14} = 64.5$ inches, see Equation (**37**).

Having decided upon a diameter of 63 inches for the magnet wheel the peripheral speed of the magnet wheel will be close to $\frac{63\times 3.14\times 375}{12}=6{,}200$ feet per minute, which is an average figure. See Table **16**.

459. Pole Arc.—The number of poles being $2p=16$, the pole pitch τ on the bore is equal to $\frac{63\times 3.14}{16}=12.35$ inches and with the assumed pole arc ratio the pole arc is equal to $12.35\times 0.65=8$ inches.

460. Dimensions of Teeth—The number of slots is equal to 96 and the slot pitch O is equal to $\frac{63\times 3.14}{96}=2.08$ inches, the narrowest part of the tooth being $r=2.08-0.75=1.33$ inches, while the mean thickness is equal to 1.38 inches.

461. Armature Length.—The useful flux per pole, according to Equation (**33**), is equal to $\frac{2000\times 10^8}{2.3\times 50\times 416}=4.2\times 10^6$ magnetic lines; so if we allow $B_t=73{,}000$ lines as magnetic density in the teeth, the effective teeth section will be $\frac{4.2\times 10^6}{73{,}000}=57$ sq. inches; and the iron length $l=\frac{57}{\frac{8}{2.08}\times 1.38\times 0.9}=12$ inches, including the paper insulation.

After providing 2 ventilating ducts of ½ inch width, the overall length of the armature will be 13 inches.

462. Armature Diameter.—The sectional area of the armature core below the slots will be equal to $\frac{4.2\quad 10}{2\times 30{,}000}=70$ sq. inches allowing a magnetic density of 30,000 lines and consequently the iron height below the slots is equal to $\frac{70}{12\times0.9}=6.45$ inches; or, with a value of 6.4 inches, the overal diameter of the armature will be $63+2(2.1+6.4)=80$ inches.

463. Pole Core Area.—For the first approximation we will assume a leakage factor of $\sigma=1.2$ so that the flux per pole will be equal to $1.2\times4.2\times10^6=5.05\times10^6$ lines.

With regard to the reasons developed in Par. **439**, the magnetic density in the pole section should not be higher than about 95,000 lines per sq. inch. The effective area of the pole core under these conditions will be $\frac{5.05\times10^6}{95{,}000}=53$ sq. inches.

Allowing for the useful magnetic leakage, we take an overall length of 12 inches, and the width of the pole stamping will be $\frac{53}{12\times0.95}=4.65$, say 4.75 inches.

464. Wheel Rim.—The material of the wheel rim is cast iron; so with regard to mechanical strength as well as the moderate saturation degree, the section of the same will be taken as 20 by 4 inches. Therefore the sectional area is equal to $20\times4=80$ sq. inches and the magnetic density $\frac{5.05\times10^6}{2\times80}=31{,}600$ lines.

465. Armature Ampere Turns.—The air gap should be chosen with the view that the overload capacity, or, in other words, the ratio between the short circuit current which corresponds to the normal excitation, and the normal load current of 72.5 amperes, should be about 1.8 to 2.

For the normal load of $\cos\varphi=1$, the total number of armature ampere conductors is equal to $1{,}248\times72.5=90{,}000$. Therefore, the total number of armature ampere turns is equal to $\frac{90{,}000}{2}=45{,}000$, or $\frac{45{,}000}{3}=15{,}000$ ampere turns per phase.

466. Normal Excitation.—With the application of Equation (**32**), the total value of the effective back ampere turns will be found equal to $2.12 \times 15{,}000 = 31{,}800$, or $\frac{31{,}800}{16} = 1970$ ampere turns per pole.

Assuming a short circuit constant of 1.15 with the specific ratio factor of 1.8 to 2, the normal excitation corresponding to 3,460 volts open circuit pressure will be about $1.15 \times 1.9 \times 1970 = 4{,}300$ ampere turns per pole.

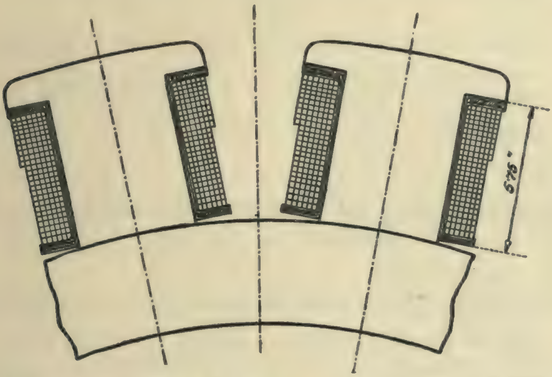

FIG. 97.—POLE WINDING OF 550 H. P., 3460 VOLT, SYNCHRONOUS 3-PHASE MOTOR.

467. Air Gap.—With the object that the normal pressure should be below the knee of the no-load characteristic, the magnetic densities in the iron parts are kept comparatively low, so that a utilization of about 80 per cent. of the total ampere turns in the air gap may be expected. This 80 per cent. amounts to about $4300 \times .8 = 3{,}440$ ampere turns; consequently with a rough approximation by means of Equation (**21**), the air gap will be $r_0 \times F_2 = 3{,}440 = \frac{\delta \times 0.313}{12 \times 8} \times 4.2 \times 10^6$, where $\delta = 0.25$ inch, and for further calculation is taken as 0.2 inch.

468. Field Winding Space.—For the determination of the pole core height, we will assume that the current density in the field winding is about 1,100 amps. per sq. inch, for an excitation of 4,300 amperes turns per pole. Therefore, with sufficient exactness, the sectional copper area of one side of a coil is equal to $\frac{4300}{1100} = 3.9$ square inches and, providing that the space factor is about 0.4, the necessary winding space for one side of a coil will be $\frac{3.9}{0.4} = 9.8$ sq. inches.

If we assume a coil depth of 1.75 inches, the pole core height is equal to $\frac{9.8}{1.75} = 5.6$ inches, consequently for convenience we fix it as 5.75 inches (see Fig. 97) with a pole shoe height of 1.25 inches.

469. Dimensions of Magnetic Circuit.—The principal dimensions of the iron body are as follows (see Fig. 98):

External diameter of the armature	80	inches.
Bore of the armature	63	“
Slot width	0.75	“
Slot depth	2.10	“
Total length of the armature, including 2 air ducts	13	“
Length of pole core	12	“
External diameter of magnet wheel	62.6	“
Pole arc	8	“
Pole shoe height	1.25	“
Total pole height	7	“
Pole core width	4.75	“
Wheel rim width	20	“
Wheel rim height	4	“

470. Leakage Factor.—It is necessary to see if the various assumptions are sufficiently exact, and the first thing to do is to calculate the leakage factor.

By means of Equation (**20**), the air gap reluctance will be found equal to

$$r_0 = \cfrac{0.313}{\cfrac{8 \times 1.33 \times 12}{2.08 \times 0.2} + \cfrac{12 \times 8 \times (0.2+0.37)}{2.08 \times (0.2+0.2)}} = \frac{8.4}{10_4}$$

Equation (**23**), gives a field leakage path reluctance of

$$r_1{}^1 = \cfrac{0.313}{\cfrac{4 \times 1.25 \times 12}{4.3} + \cfrac{4 \times 5.75 \times 12}{6} + \cfrac{4 \times 4.75 \times 5.75}{10.75}} = \frac{44.5}{10^4}$$

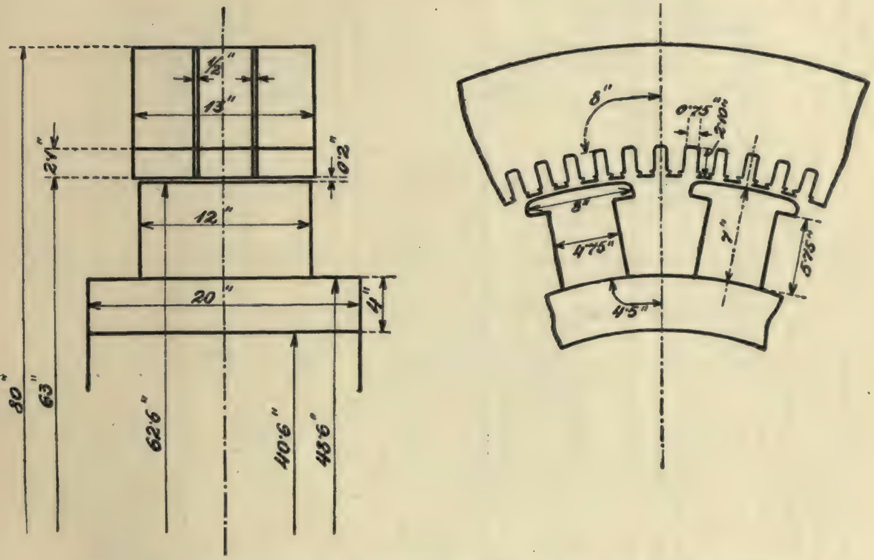

Fig. 98.—Dimensions of Magnetic Circuit, 550 h. p., 375 Revs., 50-Cycle, Synchronous 3-Phase Motor.

Therefore the leakage factor σ, is equal to $1 + \frac{r_0}{r_1{}^1} = 1.19$, say 1.20, see Equation (**26**).

471. No Load Characteristic.—The leakage factor having an assumed value, the next step to take is the calculation of the no-load characteristic. In Table **25** the various data is collected, while Fig. 99 gives the curve of the no-

TABLE 25.

E. M. F.				4500		3460		2500		1500	
ARMATURE FLUX				5.50×10^6		4.20×10^6		3.05×10^6		1.83×10^6	
FIELD FLUX				6.57×10^6		5.05×10^6		3.65×10^6		2.19×10^6	
MATERIAL AND SECTIONAL AREA OF	WHEEL RIM	CAST IRON 80	MAGNETIC DENSITIES AND CORRESPONDING AMPERE TURNS PER ONE INCH LENGTH.	41000	105	31600	62	22800	36	13700	20
	POLE CORE	0.04″ SHEET 54		122000	370	93500	62	67500	22	40500	7
	TEETH	0.02″ TEETH 57.5		96000	75	73000	26	53000	12	31600	5
	ARMATURE CORE	0.02″ SHEET 69		39800	7	30500	5	22000	3.5	13300	2
LENGTH OF MAGNETIC PATHS.	WHEEL RIM	4.5	AMPERE TURNS OF THE PATHS.	475		280		160		90	
	POLE CORE	5.75		2120		355		125		40	
	TEETH	2.10		160		55		25		10	
	ARMATURE CORE	8		55		40		28		16	
r_0		$\frac{8.4}{10^4}$		4620		3520		2560		1540	
TOTAL AMPERE TURNS PER POLE.				7430		4250		2898		1706	

load characteristic, from which it is seen that the normal terminal pressure is located at the proper place.

472. Short Circuit Constant.—For the calculation of the short circuit constant, we find from Equation (**24**), the reluctance of the armature leakage path is equal to

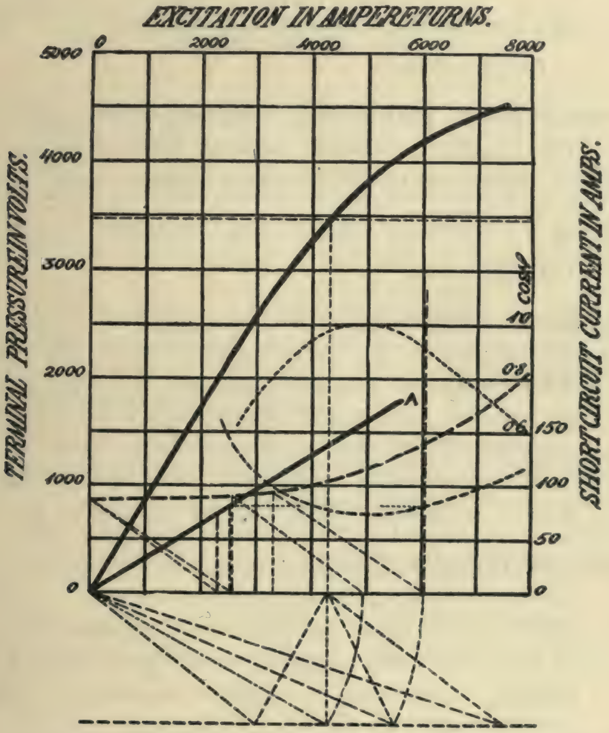

FIG. 99.—CHARACTERISTICS OF 550 H. P., 375 REVS., 50-CYCLE SYNCHRONOUS 3-PHASE MOTOR.

$$r_2{}^1=\frac{0.313}{\dfrac{4\times2.1\times12\times2.08}{0.75\times12.3}+\dfrac{4\times2.1\times1.33\,(12.3+2.08)}{12.3\times2.08}+26}=\frac{56}{10^4}$$

and the short circuit factor $k_s=1+\dfrac{r_o}{r_{2_s}^{\,1}}=1+\dfrac{8.4}{56}=1.15$, see Equation (**29**).

473. Short Circuit Characteristic.—In Fig. 99 the short circuit characteristic OA, is given by the line passing through the zero point and the point which represents 72.5 amperes armature current on the abscissa of 2,300 ampere turns. The latter value has been obtained by multiplying the normal back ampere turns per pole by the short circuit constant, and is equal to $2.12\times\frac{48\times 13\times 72.5}{3\times 16}\times 1.15=2{,}300$.

474. Overload Capacity.—Fig. 99 clearly indicates that the specified overload capacity is obtained, because the ratio between the short circuit current, which corresponds to the normal excitation and the normal current, is $\frac{4250}{2300}=1.85$.

475. The V Curve.—The **V** characteristic of the motor is determined in the manner described in Pars. **440** and **441** and Fig. 99 indicates that for the condition of normal full load and the supply of a leading current with $\cos\varphi=0.9$, the field excitation must have the value of 6,050 ampere turns. The form and course of the **V** curve is very satisfactory and may be considered as standard.

476. Field Winding.—The field winding is to be determined for a maximum pressure of 120 volts, and a maximum of 6,050 ampere turns per pole. Assuming a winding depth of 1.6 inches, the length of mean turn is found to be 38 inches. Assuming a current density of 1,600, $e=\frac{(z\times C_1)\times 2p\times L_1}{q_1}\times\frac{8}{10^7}$, from which we find a sectional area of q_1 equal to 0.0245 sq. inch.

The nearest size to this will be a No. 7 S.W.G. wire of 0.0243 sq. inch, in which the current will be equal to $0.0243\times 1600=39$ amperes. The maximum excitation requires $\frac{6050}{39}=155$ turns per pole. The maximum energy utilized in the pole winding amounts to $120\times 39=4{,}680$ watts.

477. Temperature Rise.—The total cooling surface of the field coils is equal to $O_1 = L_1 \times d \times 2p + 2b \times f \times 2p$, which in the present case is equal to $5.75 \times 38 \times 16 + 2 \times 4.75 \times 12 \times 16 = 5350$ sq. inches. The mean value of the speed is $\frac{54 \times 3.14 \times 375}{12} = 5300$ feet per minute. From Equation (**41**), the temperature rise will be equal to

$$\frac{4680 \times 100}{5350\ (1 + 0.0002 \times 5300)} = 42.5 \text{ degrees Fahrenheit.}$$

478. Armature Copper Loss.—The length of mean armature winding is equal to $L_2 = (13 + 2.1 \times 12.4)\ 2 = 78$ inches and by means of the Equation $3 \times \frac{ZL_2}{2q_2} \times \frac{8}{10^7}$ the ohmic resistance works out as $3 \times \frac{32 \times 13 \times 78}{2 \times 2 \times 0.0201} \times \frac{8}{10^7} = 0.97$ ohm. Therefore the armature copper loss on full load with $\cos \varphi = 0.9$ for the phase current, will be $81^2 \times 0.97 = 6{,}400$ watts.

479. Losses in Teeth.—The losses in the teeth are one part of the armature iron losses, and with reference to Fig. 29, and by means of equation $S \times i \times r \times l \times 0.9 \times .28 (w_h + w_e) = W_t$, it equals $850(4.2 + 0.9) = 4{,}340$ watts.

480. Losses in Core.—The weight of the armature core is equal to 4,500 lbs. and the losses therein are $4{,}500\ (1 + 0.2) = 5{,}400$ watts.

481. Temperature Rise in Armature.—The total armature losses will be $6{,}400 + 4{,}340 + 5{,}400 = 16{,}140$ watts and the corresponding cooling surface, $2{,}400 + 3{,}000 + 6 \times 1{,}900 = 16{,}800$ sq. inches. Therefore, from Equation (**40**), a temperature rise of $T_2 = 75 \times \frac{16140}{16800} = 72.5$ degrees Fahrenheit is obtained.

482. Total Losses.—The various losses in the fully loaded motor carrying a leading current with a power factor of $\cos\varphi = 0.9$, consist of the excitation energy of 4,680 watts, armature copper loss of 6,400 watts, iron losses of 9,740 watts and an assumed value for friction and ventilation losses of 6,500 watts.

483. Full Load Efficiency.—From the above the full load efficiency, see Equation (**43**), is found equal to $\frac{410000}{410000+4680+6400+9740+6500}=94\%$, which is in accordance with the specification, Par. **446.**

484. Summary of Design.—The design of this motor is very economical, as indicated by the output constant which from Equation (**39**), is .equal to $f=\frac{63^2 \times 12 \times 375}{485}$ $= 37 \times 10^3$.

The weights of the various parts are: Armature iron stampings, 850+4,500=5,350 lbs.; armature copper 630 lbs., and the field copper 760 lbs. The above weights when compared with the data in Fig. 14, indicate an economical utilization of the material.

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QUESTIONS
ON
THE DESIGN OF ALTERNATING GENERATORS
AND SYNCHRONOUS MOTORS

THE DESIGN OF ALTERNATING GENERATORS AND SYNCHRONOUS MOTORS.

---

1. What does the work of the dynamo designer generally include?
2. Name and describe the two classes of alternators which differ only in their relative excitation arrangement.
3. Give the connection diagram of (1) a separately and (2) of a self-excited alternator.
4. State the further classification of alternators with regard to their relative arrangement of (1) the armature and (2) the field magnet system.
5. Describe the different types of this classification.
6. State the particular cases in which the revolving armature type alternator finds its application.
7. State the advantages and disadvantages of the inductor type alternator; also its principal application.
8. Mention for what sizes of machines the revolving field type alternator is generally built; also state for what kind of work it is most suitable.
9. What is the average commercial efficiency of a 500 *KVA*. polyphase alternator for full and half load?
10. What is the efficiency of a 500 *KVA*. single phase alternator on full and half load?
11. Give the usual voltage drop of an alternator working under full load conditions with the different power factors of $\cos\varphi = .8$ $\cos\phi = .6$ and $\cos\varphi = .1$; and also define the voltage drop as specified above.

12. What are the usual number of slots allowed per pole?

13. State the average permissible temperature rise for the different parts of a generator?

14. What is the usual value of short circuit current in a well designed alternator, and why should it not be exceeded?

15. What degree of insulation should the armature and field coils possess?

16. Mention some of the mechanical features of a modern alternator.

17. What benefits are obtained from the use of higher efficiencies than those given in Tables **1** and **2** in the instruction book, from the central station engineer's point of view as well as from that of the manufacturer?

18. State the advantage and disadvantage of a smaller voltage drop than that given in answer to Question **11.**

19. What advantage has an alternator with the E. M. F. of practically a sinusoidal wave form?

20. What would be the disadvantage in having a greater number of slots per pole than that given in answer to Question **12?**

21. Up to what size is the carcase or shell cast in one piece and why is this not done for larger machines?

22. What material is employed for armature core stampings; what is their usual thickness, and how are they assembled?

23. What is the object of laminating the armature core?

24. What is the most reliable insulation used between the armature core stampings? State the usual thickness of same.

25. What is understood by the effective iron volume of the armature core? State its average value.

26. What means are used to obtain perfect solidity of the armature core around the teeth?

27. Why is the inner surface of the armature core not machined?

28. How are the armature stampings made and arranged for armatures up to 2 feet in diameter? State the usual arrangement of stampings for machines of larger sizes.

29. Describe the armature construction which gives good ventilation.

30. State the various kinds of slots and the most favorable shapes used in modern alternators.

31. What is understood by the space factor of a slot?

32. Give the average slot space factor of a 600 KVA. 5,000 volt alternator.

33. What considerations influence the choice of the armature conductors for large current machines?

34. What are the principal properties of an insulation material which is placed between the coils and the iron core?

35. What should be the minimum thickness of micanite tubes employed for a working pressure of 6,500 volts?

36. What principal quality has press board (press spahn) and what thickness of same should be used for a pressure of 4,500 volts?

37. What precautions are necessary in arranging the coils which are in close proximity to the surrounding iron parts of a high tension machine?

38. Show by a sketch the arrangement of the armature conductors in a single slot of a high tension alternator; each slot is to take 6 wires in radial direction and 3 in width.

39. In what cases are cast steel poles advantageously applied? Where and why are laminated poles used?

40. What is the usual thickness of the sheet iron employed in laminated poles?

41. How are the laminations insulated from each other?

42. State the average proportion of the effective iron section to the total volume of a pole.

43. State the usual method of winding the field coils of revolving field type alternators.

44. What is the usual current density between gun metal slip rings and carbon or copper brushes?

45. Give the average weights of material used in an 850 KVA., medium speed, 50-cycle polyphase alternator.

46. What would be the approximate cost of labor for this machine in England?

47. State the relation between KW. and KVA.

48. What is the rated capacity of an alternator which supplies 800 KW. to a motor circuit having a power factor of $\cos \varphi = .8$?

49. Give the formula expressing the output of an alternator in horsepower when its efficiency and capacity in KW. are given.

50. A 350 KW. polyphase alternator with an efficiency of 93.5% at full load supplies current to motor and lamp circuits, with a power factor of $\cos \varphi = .85$. What is the rated capacity of this alternator and that of its prime mover?

51. What would be the rated capacity of the prime mover when the same alternator in Question **50** supplies energy to a lighting circuit only?

52. State the formula giving the output of a single phase alternator having (1) an open armature winding and (2) a closed armature winding.

53. Give the formula determining the output of a two phase alternator, having (1) an open armature winding of two independent phases, and (2) a closed armature winding.

54. What will be the current in each phase of an 800 KVA. 4,000 volt two phase alternator with two independent phases?

55. Considering the same alternator as in Question **54** with a closed armature winding, give the voltage and current per phase.

56. Give the formula expressing the output (1) of the delta, and (2) star connected three phase alternator.

57. State the voltage and armature current per phase of a 420 KVA. alternator when working, (1) as a single phase generator; (2) as a two phase generator; and (3) as a three phase generator, with a line voltage of 600 volts.

58. What are the guiding factors in choosing the speed of an alternator?

59. Why should the application of an odd number of pole pairs be avoided?

60. A 12-pole direct coupled alternator has to produce a current having a frequency of 60 cycles; what should be the speed of the prime mover?

61. What difficulties are presented in designing low and high frequency alternators?

62. State the different constant and variable losses of an alternator.

63. An alternator has to be designed with the object of possessing a nearly constant efficiency for a wide range of external load. In such a case what constant and variable losses are to be taken?

64. Give the formula expressing the efficiency of an alternator.

65. In a 400 KVA. three phase alternator the following losses have been measured:

Copper loss in the armature	5,000 watts
Iron losses	9,000 "
Friction and ventilation losses	6,000 "
Field copper losses at full load	7,000 "
Field copper losses at half load	4,500 "

What is the efficiency of this alternator (1) at full and (2) at half-load?

66. Give the average friction and ventilation losses of an 800 KVA. alternator.

67. State the formula which gives the bearing friction losses in watts of an alternator.

68. What are the bearing friction losses of a 770 KVA. alternator running at 214 r. p. m. having a shaft diameter inside the bearings of $d = 9$ inches, and an effective bearing length of $l = 20$ inches?

69. State the different items of iron loss in an alternator.

70. Give the limits of the magnetic armature core densities for a frequency of from 25 to 120, in the form of two curves.

71. In what approximate proportions are the magnetic densities distributed in the armature core and teeth?

72. What average amount of losses per pound of effective armature iron is to be anticipated in a commercial alternator?

73. Give the approximate iron loss of a 250 KVA. alternator, and state the amount of iron losses per pound, using the respective curves of Figs. 14 and 28 of the Instruction Paper.

74. In the case of a 400 KVA. alternator for a frequency of 50, it has been calculated that the amount of teeth iron should be 580 pounds for a saturation of 84,000 lines per square inch; the amount of armature iron, 4,200 pounds for a saturation of 30,000 lines per square inch; and that the laminations should have a thickness of 0.2 inch. Find the total amount of armature iron losses in this alternator.

75. What extra factor may considerably affect the resulting eddy current losses?

76. Give the usual armature copper losses of a 600 KVA. alternator.

77. What usual current densities are employed in the armature conductors of an alternator?

78. Give the formula for determining the power lost in the armature winding of an alternator.

79. Give the formula for determining the ohmic resistance of the armature winding of an alternator.

80. Give the formula for determining the mean length of an armature turn.

81. A three phase alternator designed for 50 amperes at a medium voltage has in its star connected armature 216 turns per phase. Each conductor consists of two parallel connected No. 9 S. W. G. wires, each wire having a section of .0163 square inch. The armature core length is 10 inches and the pole pitch is 14½ inches. What is (1) the mean length of a turn; (2) the total resistance of all three phases; and (3) the resulting copper losses for the normal current of 50 amperes?

82. What is the usual amount of excitation losses in a 500 KVA. alternator?

83. For what output must the exciter of an alternator be designed?

84. Give the formula for determining the power utilized in the field winding of an alternator.

85. The maximum excitation current of a 400 KVA. alternator is 260 amperes and the resistance of the field coils is .10 ohm. What will be the power absorbed in the field winding of this alternator?

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86. What is understood by the term "voltage drop" in an alternator and what machine characteristics are used in its investigation?

87. What is understood by the "open circuit characteristic"?

88. Give the formula stating the relation between the field ampere turns and the useful armature flux.

89. Plot the no-load characteristic and the apparent resistance curve for an open circuit test of the following data:

Excitation in ampere turns	*Armature pressure*
1,000 ampere turns	820 volts
2,000 "	1,620 "
3,000 "	2,340 "
4,000 "	2,960 "
5,000 "	3,380 "
6,000 "	3,600 "

90. What is understood by the "short circuit characteristic"?

91. How is the short circuit characteristic of an alternator determined experimentally?

92. Give the equation of the short circuit characteristic.

93. What is the load characteristic of an alternator?

94. What is the cause of inductive voltage drop in an alternator and how is it expressed? Give the formula of the load characteristic.

95. From the experimental machine characteristics of a 375 KVA. polyphase alternator as given in answer to Question *89*, determine the inductive cos $\varphi = 0$ load characteristic for 60 amperes armature current, which on the short circuit characteristic corresponds to 1,800 ampere turns excitation, by applying the approximate method of Prof. Arnold.

96. Give the exact expression of the inductive load characteristic which takes into account the different degrees of magnetic saturation of the alternator.

97. Apply the graphical method for determining the inductive cos $\varphi = 0$ load characteristic of an alternator, the data of which is given in Question *95*.

98. Determine the drop for the same armature current as given in Question *95* but with a power factor of cos $\varphi = .8$.

99. What principal elements affect the inherent regulation of an alternator?

100. State the different paths of one closed magnetic circuit in an alternator.

101. Represent graphically a closed magnetic circuit of an alternator.

102. Give the symbolical expression for magnetic reluctance.

103. Give your reasons for the necessity of an accurate determination of the machine characteristics in designing an alternator, such as the example given in Paragraphs **140** and **141** of the Instruction Book.

104. With reference to Fig. 42 in the Instruction Book, give the symbolical expression of magnetic reluctance of the field system of one pole and calculate same from the dimensions of the particular 12-pole machine illustrated in the accompanying Fig. 1.

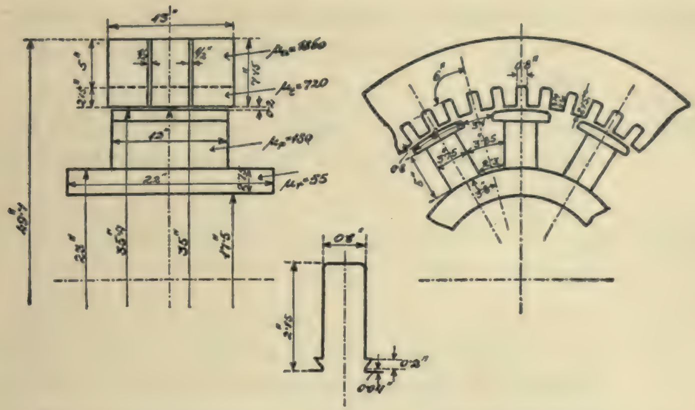

FIG. 1.—DIMENSIONS OF A 175 KVA., 400 REVS., 40-CYCLE, 3-PHASE ALTERNATOR.

105. Give the symbolical expression of the air gap reluctance per pole and calculate same from the dimensions given in Question *104*.

106. Give the symbolical expression of the armature path reluctance and calculate same from the data given in Question *104*.

107. Give the symbolical expression of the reluctance of the field leakage path and calculate same from the data given in Question *104*.

108. What is the symbolical expression of reluctance of the armature leakage path? Calculate same from the data given in Question *104* if the length of the inactive wire is $a + n + 2l_1 = 15$ inches.

109. Give the simplified formula of the leakage factor and calculate same from the data given in Question *104*.

110. Give the simplified form of the short circuit current factor k_s and calculate same from the particulars given in answer to the previous six questions.

111. Give the formulæ stating the value of the armature ampere turns for single-phase, two-phase and three-phase alternators.

112. Calculate the back ampere turns of a 180 KVA., 220 amperes, star connected three-phase alternator, having 36 turns per phase.

113. Give the equation for the generated E. M. F. of an alternator.

114. A 400 KVA. revolving field type star connected 50-cycle three-phase alternator generating a phase pressure of 2,040 volts has 432 armature conductors per phase and a form factor of 2.3. What will be the useful flux per pole of this alternator?

115. Give the general symbolical expression for the field ampere turns per pole.

116. For a certain alternator it has been found necessary to use a useful flux per pole of 4.12×10^6 lines and a leakage factor of 1.25. What will be the flux value in the field system?

117. What is the number of ampere turns which is required to drive 50,000 magnetic lines per square inch through a cast iron path having a length of 5 inches?

118. An alternator has an external magnet wheel diameter of 54.6 inches and 12 poles. What is the pole pitch of this machine?

119. The pole arc length of the above alternator is 8.75 inches. What will be the pole arc ratio?

120. Upon what principal elements does the wave form of the E. M. F. of an alternator depend?

121. What is understood by "long coil windings"?

122. State the best values of the pole arc ratio for alternate pole and equipole alternators.

123. A two-phase alternator has a pole arc ratio of .66 and a coil breadth ratio of $\frac{2}{9}$. State the value of the form factor of this machine.

124. A two-phase alternator with 64 poles has an armature containing 256 slots. The pole arc is 5 inches and the pole pitch 8.3 inches. What will be the value of the form factor of this alternator?

125. Calculate the useful armature flux which is required to generator a phase pressure of 3,500 volts at the terminals of the two-phase alternator for which the open circuit characteristic is calculatetd in Example **23**, Par. **178** of the Instruction Book.

126. State the formula which has been applied for the calculation of the leakage factor, in the example given in Example **23**, Par. **178** of the Instruction Book.

127. What tooth thickness should be inserted in the formula, and give the section of same?

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128. State the different problems which present themselves in the design of alternators.

129. State the principal item which influences the economical application of material for a certain regulation.

130. What is the flux value per pole of a 150 KVA. alternator, running at a speed of 600 revs. per minute and generating a current at 60 cycles?

131. Give the modified symbolical expression of the fundamental Equation (**33**), indicated in Par. **165** of the Instruction Book.

132. What is understood by the peripheral density of an alternator? State the symbolical expression for same.

133. A 400 KVA. star-connected three phase alternator, running at a speed of 500 revs. per minute and generating a line pressure of 3,500 volts, has an armature bore of $D = 55$ inches and 432 armature conductors per phase. Calculate the peripheral density of this alternator.

134. What does the choice of the diameter of the alternator according to its peripheral density take into consideration?

135. What is the peripheral density of a 600 KVA. 50-cycle polyphase alternator?

136. What would be the peripheral density of the alternator given in Question **135** when generating a current at 25 cycles?

137. The alternator in Question **135** is destined to supply high tension at a frequency of 50 cycles. What will be its peripheral density under these circumstances?

138. Give the average peripheral densities of a 200, a 500 and an 800 KVA. single phase alternator, each generating current at 50 cycles.

139. For a low speed 400 KVA. medium tension, 50 cycle, three phase alternator, the total armature conductor value has been found to be 85,540. What will be the approximate armature bore of this machine?

140. State the limits of usual peripheral speeds of standard alternators.

141. Give the formula for the peripheral speed of the magnet wheel of an alternator.

142. State the formula which checks the leading dimensions of alternators in terms of their outputs.

143. A 400 KVA. 500 revs. polyphase alternator, has an armature bore of 55 inches and the iron length with its paper insulation measures 9.5 inches. Calculate the output factor of this alternator.

144. Give the output factor of an 800 KVA. polyphase alternator by using the curve in Fig. 64 of the Instruction Book.

145. What approximate output will be delivered by a 500 KVA. polyphase alternator, if the same is designed for supplying a single phase current?

146. A 500 KVA. polyphase alternator generates a phase pressure of 5,000 volts. What will be the obtainable output of the same type of machine when designed to deliver a phase pressure of 10,000 volts?

147. What is the reason of the decreasing output with increasing voltage?

148. Which items are chiefly affected by the ratio between pole arc and pole pitch?

149. What special care is to be taken in determining the slot dimensions of an alternator?

150. State the principal disadvantage of high pole cores.

151. What is the maximum allowable winding depth of the field coils?

152. What should be the average specific cooling surface of the armature per watt loss?

153. Mention the different parts of the armature of an alternator which provide cooling surface.

154. State the formula for determining the temperature rise of the armature.

155. What should be the average specific cooling surface of the magnet wheel per watt excitation loss?

156. State the formula for determining the temperature rise of the magnet wheel.

157. The normal excitation current of a 12-pole alternator is 244.5 amperes. The field coils have a total resistance of .0865 ohm. The external cylinder surface and the two sectional areas of one pole core, which carries a coil consisting of flat edge wound copper strips, offer a cooling surface of 350 square inches. The peripheral speed of this alternator is 7,150 feet per minute. Calculate the temperature rise of the magnet wheel of this alternator.

158. What average amount of field ampere turns should be allowed for the air gap?

159. What condition does the application of a small air gap affect?

160. What condition speaks in favor of large air gaps?

161. Follow the design of the 400 KVA. three phase alternator for which the necessary data is given in Pars. **210** to **268**, step by step, and state the principal formulæ which have been applied in calculating the respective values.

DESIGN A REVOLVING FIELD TYPE SINGLE PHASE ALTERNATOR TO THE THE FOLLOWING SPECIFICATIONS BY ANSWERING QUESTIONS 162 TO 206.

Output = 75 KVA.
Speed = 600 revs.
Frequency = 60 cycles.
Terminal pressure = 1,000 volts.
Load-power, factor, cos $\varphi = .95$.
The efficiency must not be below 89% at full inductive load
The voltage drop shall not exceed 12% at full inductive load.
The temperature rise on any part of the machine shall not exceed 75 degrees Fahrenheit.
For the armature winding the long coil type in open slots is to be applied and the armature core is to be made up of .02 inch laminæ.
For the poles .04 inch laminæ are to be applied.

162. Determine the necessary number of poles.

163. Calculate the horsepower of the steam engine to which this alternator has to be coupled.

164. By means of Fig. 62 of the Instruction Book, determine the most suitable total flux to be applied for this single phase alternator. It is to be noted that on account of this machine being single phase the most suitable flux will correspond to an output which is about 30 per cent. higher than the actual one.

165. An average form factor of $k = 2.0$ being assumed, calculate by means of Equation **35** of the Instruction Book the necessary number of armature-ampere-conductors corresponding to the flux ascertained in the preceding question.

166. Calculate the full load current and determine the approximate number of total armature conductors.

167. The total number of slots, of which only 24 contain the armature winding, being fixed at 36, determine the number of conductors per slot. It is to be noted that with regard to a convenient winding arrangement the higher, even number of conductors per slot above that obtained by calculation is to be taken.

168. With the number of conductors per slot ascertained in the preceding question, calculate the corrected number of total armature conductors.

169. With the above stated form factor value, $k = 2.0$, and the corrected number of total armature conductors, calculate, by means of Equation **33** of the Instruction Book, the corrected useful flux per pole.

170. By means of Fig. 63 and Equation **37** of the Instruction Book, calculate the approximate armature bore of this alternator. It is to be noted that the peripheral density of this single phase alternator will be about 20 per cent. lower than that of a polyphase alternator of equal size.

171. The armature bore of this machine being definitely fixed at $D = 36$ inches, calculate by means of Equation **38** of the Instruction Book the approximate peripheral speed of the magnet wheel, neglecting the small difference existing between the armature bore and the external diameter of the magnet wheel, that is, the air gap.

172. Allowing a current density of 2,200 amperes per square inch for the armature conductors, determine the most suitable size for same, but do not employ thicker wire than .16 inch diameter. Calculate also the number of wires per slot.

173. Determine the most suitable slot-shape, considering the best ratio of slot width to slot height. Make a sketch showing the different slot dimensions and the arrangement of the wires. Micanite insulation of .05 inch thickness and a fixing wedge of .2 inch thickness are to be applied.

174. Calculate the mean thickness of a tooth.

175. By means of Fig. 27 of the Instruction Book, calculate the approximate effective teeth section belonging to a pole.

176. Assuming an average pole arc ratio of $\frac{a}{\tau} = .60$ and that about 10 per cent. of the total armature length is taken up by insulation paper, calculate the overall length of the armature including a ventilation duct of .5 inch width.

177. With reference to Fig. 26 of the Instruction Book, determine the necessary effective armature core section and its height above the slot.

178. Assuming a pole core density of 105,000 lines per square inch and an average leakage factor of $\sigma = 1.25$, calculate the effective pole core section and the necessary pole width, taking into consideration that about 5 per cent. of the pole core length is taken up by insulation material.

179. The magnetic density in the cast iron rim should be about 40,000 lines per square inch; calculate its necessary section accordingly.

180. Determine the rim dimensions by allowing 2.75 inches projection on each side of the magnet pole for support and protection of the field coils.

181. By means of Equation **30** of the Instruction Book, cal-calculate the value of the effective back ampere turns.

182. Calculate the value of the necessary field ampere turns per pole corresponding to the normal open circuit pressure, taking into consideration that, with regard to the specified voltage drop, the normal excitation ampere turns must be about 2.5 times greater than the normal effective back ampere turns.

183. The current density in the field winding being chosen at 1,100 amperes per square inch, and the space factor assumed at .4, calculate the approximate necessary winding space of an excitation coil.

184. Allowing a maximum winding depth of 1.5 inches, calculate the approximate useful pole height.

185. Make the poleshoe height $c = 1$ inch and collect the principal, established dimensions of this machine, in a manner similar to that shown in Par. **314** of the Instruction Book. A dimensioned sketch similar to Fig. 74 of the Instruction Book is also to be given.

186. By means of Equation **21** of the Instruction Book as a first approximation, calculate the air gap value, assuming that about 70% of the normal field ampere turns are consumed in the air and allowing a reduction of the air gap of 10% on account of the effective iron section being reduced by the slot openings, which consideration is entirely neglected by the application of Equation **21**.

187. By means of Equation **26** of the Instruction Book, calculate the leakage factor of this alternator and see whether the value so obtained is in accordance with the one previously assumed.

188. Calculate four points of the no-load characteristic for 600, 800, 1,000 and 1,200 volts and collect the different data in table form similar to Table 19 of the Instruction Book. The different path lengths are to be taken from a full sized sketch, or may be calculated.

189. By means of Equation **29** of the Instruction Book, calculate the short-circuit constant for this alternator, determining first the reluctance of the armature leakage path r_2^1. For this purpose take the projecting out part of the armature winding $2l_1 = 7$ inches.

190. By means of Equation **15** of the Instruction Book, calculate the amount of field ampere turns per pole which corresponds to the normal short circuit current of the armature.

191. Plot the no-load and short circuit characteristics, applying the following scales: 1,000 ampere-turns = 1 inch; 250 volts terminal pressure = 1 inch; 75 amperes armature current = 1 inch.

192. In the same figure determine graphically the voltage drop for the normal armature current of 75 amperes and for a power factor of $\cos \varphi = .95$.

193. For the full $\cos \varphi = .95$ load, state the required number of field ampere turns per pole. (To be taken from the figure given in the preceding question.)

194. Assuming a winding depth of 1.5 inches and a thickness of about .25 inch for the metal bobbin and its insulation on each side of the pole core, calculate as a first approximation the length of a mean turn of the field coil.

195. Taking into consideration a margin of 16% excitation, calculate for 100 volts excitation pressure the necessary conductor section of the field coils and choose the most suitable size of wire in S.W.G.

196. Allowing for the maximum excitation a current density of 1,600 amperes per square inch, calculate the necessary maximum excitation current and the resulting number of turns per pole.

197. State the most suitable arrangement of turns, and make a sketch half full size, of two adjacent pole pieces with their respective windings. For this purpose assume that in the radial direction the total room taken up by the bobbins and end plates is .825 inch.

198. Calculate the excitation loss corresponding to the normal excitation of 4,060 ampere turns per pole.

199. Calculate the hot armature resistance and determine the armature copper loss at full load.

200. Calculate the weight of the teeth, and the iron losses in same.

201. Calculate the weight of the armature core, and the iron losses in same.

202. By means of Equation **8** of the Instruction Book, calculate the full load efficiency of this alternator.

203. By means of Equation **41** of the Instruction Book calculate the temperature rise on the field coils. For this purpose take the constant $K = 120$, on account of the field coils being very near together, as may be seen from the sketch.

204. By means of Equation **40** of the Instruction Book, calculate the temperature rise on the armature.

205. By means of Equation **39** and Fig. 64 of the Instruction Book, compare the economy in dimensions with standard designs.

206. Collect in tabular form the different data of this single phase alternator. As an example take Table 23 of the Instruction Book.

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DESIGN A REVOLVING FIELD TYPE THREE-PHASE ALTERNATOR TO THE FOLLOWING SPECIFICATION:

Output = 250 KVA.
Speed = 375 Revs.
Frequency = 50 Cycles.
Terminal pressure = 3,300 Volts.
Connection of armature = Star.
Load power factor cos φ = .80.

The efficiency shall not be below 92% at full inductive load.

The voltage drop shall not exceed 16% at full inductive load.

The temperature rise on any part of the machine shall not exceed 75 degrees Fahrenheit.

For the armature winding the long coil type in open slots is to be applied and the armature core is to be made up of .02 inch laminæ.

For the poles .04 inch laminæ are to be applied.

207. Determine the necessary number of poles.

208. Calculate the output of the prime mover to which this alternator has to be coupled.

209. By means of Fig. 62 of the Instruction Book, determine the most suitable flux to be applied for this alternator.

210. The number of slots per pole and phase being chosen to 2 and the pole arc ratio to $\frac{\alpha}{\tau} = .65$, state by means of Table

14 of the Instruction Book the value of the form factor which is to be applied in the present design.

211. By means of Equation **35** of the Instruction Book, calculate the necessary total number of armature ampere conductors corresponding to the flux already given.

212. Calculate the full load current and determine the approximate number of armature conductors.

213. The number of slots per pole and phase being, as already stated, fixed at 2, calculate the number of conductors per slot. It is to be noted that with regard to a perfect winding arrangement the next lower, even number of conductors per slot below that obtained by calculation is to be taken.

214. The exact number of conductors per slot being given to the preceding question, calculate the corrected number of total armature conductors and the amount of conductors per phase.

215. By means of Equation **33** of the Instruction Book, calculate the corrected useful flux per pole.

216. By means of Equation **37** and Fig. 63 of the Instruction Book, calculate the approximate armature bore of this alternator.

217. The armature bore of this alternator being definitely fixed at $D = 50$ inches, check by means of Equation **38** of the Instruction Book the peripheral speed of the magnet wheel, neglecting the small difference existing between the armature bore and the external diameter of the magnet wheel, that is, the air gap.

218. The allowable current density for the armature conductors being fixed at 2,000 amperes per square inch, calculate the necessary conductor section and state the most suitable S.W.G. size for same, but do not employ thicker wire than .16 inch diameter.

219. Determine the most suitable slot shape, considering the good ratio of slot width to slot depth, and give a dimensioned sketch showing the arrangement of the wires. Micanite insulation of .07 inch thickness and a fixing wedge of .25 inch thickness are to be applied.

220. Determine the mean thickness of a tooth.

221. With reference to Fig. 27 of the Instruction Book, calculate the approximate effective teeth section belonging to a pole.

222. Assuming an average pole arc ratio of $\frac{\alpha}{\tau} = .65$, and that about 10% of the total armature length is taken up by paper insulation, calculate the resulting armature length.

223. The armature length, including 10% for paper insulation, being definitely fixed to 13 inches, state its overall length, including 2 ventilation ducts, each of .5 inch width.

224. With reference to Fig. 26 of the Instruction Book, determine the necessary effective section of the armature core and its height above the slot.

225. Assuming a pole core density of 95,000 lines per square inch and an average leakage factor of $\sigma = 1.2$, calculate the effective pole core section and the necessary pole width, taking into consideration that about 5% of the pole core length is taken up by insulation material.

226. The magnetic density in the cast iron rim should be about 45,000 lines per square inch; calculate its necessary section accordingly.

227. Determine the rim dimensions, allowing 1.5 inch projection on each side of the magnet pole for support and protection of the field coils.

228. By means of Formula **32** of the Instruction Book, calculate the value of effective back ampere turns.

229. Calculate the amount of necessary field ampere turns per pole corresponding to the normal open circuit pressure, considering that with regard to the specified voltage drop the normal excitation ampere turns must be about 2.25 times greater than the normal effective back ampere turns.

230. The current density in the field winding being chosen at

1,000 amperes per square inch and the space factor assumed at .4, calculate the approximate necessary winding space on one side of the excitation coil.

231. Assuming a maximum allowable winding depth of 1.75 inches, calculate the approximate useful pole height and fix it afterward definitely at $d = 5$ inches.

232. Make the pole shoe height $c = 1.20$ inches, and collect the principal established dimensions of this alternator in a manner similar to that of the previous design in the form of a table.

233. As a first approximation, calculate the air gap value by means of Equation **21** of the Instruction Book, assuming that about 70% of the field ampere turns are consumed in the air and allowing a reduction of the air gap of about 20 per cent. on account of the effective iron section being reduced by the slot openings, which consideration is entirely neglected by the application of Equation **21**.

234. By means of Equation **26** of the Instruction Book, calculate the leakage factor of this alternator and see whether the value so obtained is in accordance with the one previously assumed above.

235. Calculate 4 points of the no-load characteristic for 2,000, 2,800, 3,300 and 3,800 volts and collect the different data in tabular form, similar to that given in the preceding design. The different path lengths which must be known are to be taken from a full-sized sketch, or may be calculated.

236. By means of Equation **29** of the Instruction Book, calculate the short-circuit constant for this alternator, determining first the reluctance of the armature leakage path. For this purpose take the projecting-out part of the armature winding $2l_2 = 11$ inches.

237. By means of Equation **15** of the Instruction Book, calculate the amount of field ampere turns per pole which corresponds to the normal short-circuit current of the armature.

238. Plot the no-load and short-circuit characteristics of this alternator, applying the following scales:

1,000 ampere turns excitation = 1 inch.
1,000 volts terminal pressure = 1 inch.
40 amperes armature current = 1 inch.

239. In the same drawing made in answer to Question **238**, determine graphically the voltage drop for the normal armature current of 44 amperes, the power factor being cos $\varphi = .80$.

240. Assuming a total winding depth of 1.6 inch and a thickness of about .25 inch for the metal bobbin and its insulation on each side of the pole core, calculate as a first approximation the length of a mean turn of the field coil.

241. Taking into account a margin of about 10 per cent. excitation, calculate the necessary conductor section of the field winding for 120 volts excitation pressure, choosing the most suitable size of S.W.G. wire.

242. Allowing for the maximum excitation a current density of 1,600 amperes per square inch, calculate the maximum necessary excitation current and the number of turns per pole.

243. State the most suitable arrangement of the excitation turns and make a sketch, half full size, of two adjacent pole pieces, showing their respective windings, assuming that in the radial direction the total room taken up by the bobbins and end plates is about .80 inch.

244. Calculate the excitation loss corresponding to the full cos $\varphi = .80$ load of the alternator.

245. Calculate the armature resistance (hot) and determine the armature copper loss at full load.

246. Calculate the weight of the teeth and the iron losses in same.

247. Calculate the weight of the armature core (without the teeth) and the iron losses in same.

248. By means of Equation **8** and Fig. 25 of the Instruction Book, calculate the full load efficiency of this alternator.

249. By means of Equation **41** of the Instruction Book, calculate the temperature rise on the field coils.

250. By means of Equation **40** of the Instruction Book, calculate the temperature rise on the armature.

251. By means of Equation **39** and Fig. 64 of the Instruction Book, compare the economy in dimensions of this alternator with standard designs.

252. By means of Fig. 14 of the Instruction Book, compare the weight of the armature stampings with that of an average standard design.

253. By means of Fig. 14 of the Instruction Book, compare the total weight of copper employed (armature and field winding) with that of an average standard design.

254. Collect in tabular form the different data of this three-phase alternator in a manner similar to that done for the preceding example.

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THE DESIGN OF ALTERNATING GENERATORS AND SYNCHRONOUS MOTORS.

255. What is a synchronous motor?

256. Name the principal characteristic properties of a synchronous motor.

257. Give the connection diagram of a three phase synchronous motor receiving its current from a 110 volt circuit.

258. State the principal advantages and disadvantages of synchronous motors.

259. What condition is necessary in order that the motor shall maintain an absolutely constant speed?

260. What is the average momentary overload capacity of standard synchronous motors?

261. State the different kinds of starting arrangements usually employed for synchronous motors.

262. By what means can a motor be made to start up, without the use of an outside starting arrangement?

263. What is the obtainable starting torque with this particular arrangement?

264. Calculate the input in KVA. and the current per phase, of an 800 H.P., 4,000 volts, 50 cycles, two phase synchronous motor, which has an efficiency of 96 % at full load with a power factor of $\cos \varphi = .95$.

265. State the most practical way of determining the approximate overload capacity of a synchronous motor.

266. Give the formula for the approximate maximum load capacity of a synchronous motor.

267. What should be the maximum load capacity of a synchronous motor driving a continuous current dynamo for accumulator charging?

268. Give the approximate maximum load capacity of the two phase synchronous motor referred to in Question 264, when the short circuit current for normal excitation is 163.6 amperes.

269. What are the two necessary characteristics for determining the excitation current for different power factors?

270. What form should the **V**-characteristic have with regard to the steady running of a synchronous motor?

271. Define the efficiency of a synchronous motor and state the formula for same.

272. Calculate the half load efficiency of the 450 H P. synchronous motor, for which the different losses are indicated in Fig. 95 of the Instruction Book. The power factor being assumed equal to $\cos \varphi = 1$.

DESIGN A REVOLVING FIELD TYPE TWO-PHASE SYNCHRONOUS MOTOR TO THE FOLLOWING SPECIFICATION.

Output = 300 *HP.*
Speed = 240 *Revs.*
Frequency = 40 *cycles.*
Terminal pressure = 2200 *volts.*
Connection: Two independent circuits.

This motor to be capable of carrying a leading current of $\cos \varphi = .90$ *at full load.*

The efficiency shall not be below 91.5% *for the specified working conditions.*

The temperature rise on any part of the machine shall not exceed 75 *degrees Fahrenheit.*

The momentary overload capacity shall be about 2.25 *the normal capacity, the motor being normally excited.*

For the armature the long coil type in open slots is to be applied, and the armature core is to be made up of .02 *inch laminae, whilst for the poles* .04 *inch laminae are to be applied.*

273. By means of Equation **7** of the Instruction Book, calculate the necessary number of poles.

274. Calculate the electrical input at full load, the armature carrying a leading current of cos. $\varphi = .90$.

275. By means of Fig. 62 of the Instruction Book, determine the most suitable total flux to be applied for this two-phase synchronous motor.

276. With two slots per pole and phase and a pole arc ratio of $\frac{a}{\tau} = .60$ state by means of Table 14 of the Instruction Book the value of the form factor which is to be applied in the present design.

277. By means of Equation **35** of the Instruction Book, calculate the necessary total number of armature conductors corresponding to the flux determined.

278. Calculate the full load current per phase and determine the approximate total number of armature conductors.

279. The number of slots per pole and phase being 2, as already pointed out, calculate the number of conductors per slot. It is to be noted that with regard to a perfect winding arrangement the next higher, even number of conductors per slot above that obtained by calculation is to be taken.

280. The exact number of conductors per slot being given in answer to the preceding question, calculate the corrected number of total armature conductors and the amount of conductors per phase.

281. By means of Equation **33** of the Instruction Book, calculate the corrected useful flux per pole.

282. By means of Equation **37** and Fig. 63 of the Instruction Book, calculate the approximate armature bore of this synchronous motor.

283. The armature bore of this machine being definitely fixed at $D=71$ inches, check, by means of Equation **38** of the Instruction Book, the peripheral speed of the magnet wheel, neglecting the small difference existing between the armature bore and the external diameter of the magnet wheel, that is, the airgap.

284. The maximum allowable current density for the armature conductors being fixed at 2,000 amperes per square inch, calculate the necessary conductor section and state the most suitable S. W. G. size for same, but do not employ thicker wire than .16 inch diameter (bare). Calculate also the resulting total number of wires to be placed in a slot.

285. Determine the most suitable slot shape, taking into consideration the "good ratio" of slot width to slot depth, and give a dimensioned sketch, showing the arrangement of the wires. Micanite insulation of .06 inch thickness and a fixing wedge of .25 inch thickness are to be applied.

286. Determine the mean thickness of a tooth.

287. With reference to Fig. 27 of the Instruction Book, calculate the approximate effective teeth section belonging to a pole.

288. Assuming, as already mentioned, an average pole arc ratio of $\frac{a}{\tau} = .60$, and that about 10% of the total armature length is taken up by paper insulation, calculate the resulting armature length.

289. The armature iron length, including 10% for paper insulation, being definitely fixed to 9.5 inches, state the overall length of same, making provision also for two ventilation ducts, each of .5 inch width.

290. With reference to Fig. 26 of the Instruction Book, determine the necessary effective section of the armature core and its height above the slot.

291. The pole core length being fixed at 9.5 inches and assuming a pole core density of 95,000 lines per square inch and an average leakage factor of $\sigma = 1.20$, calculate the effective pole core section and the resulting pole width, taking into consideration that about 5% of the pole-core length is taken up by insulation material.

292. With an average magnetic density in the cast iron rim of $B_1=$ 45,000 lines per square inch, calculate its necessary section.

293. Determine the rim dimensions by allowing 2.25 inches projection on each side of the magnet pole for support and protection of the field coils.

294. By means of Equation **31** of the Instruction Book, calculate the value of effective back-ampere-turns.

295. Calculate the value of the necessary field ampere turns per pole corresponding to the normal open circuit pressure, considering that with regard to the specified momentary overload capacity the normal excitation ampere turns must be about 2.25 times greater than the normal effective back-ampere-turns.

296. The current density in the field winding being chosen at 1,300 amperes per square inch and the space factor assumed at .40, calculate the approximate necessary winding space on one side of an excitation coil.

297. Assuming a maximum allowable winding depth of 1.5 inch, calculate the useful pole height.

298. Make the poleshoe height $c=1.2$ inch and collect in tabular form the principal dimensions of this synchronous motor thus far established, in a manner similar to that of the two preceding alternator designs. Give also a dimensioned sketch similar to Fig. 74 of the Instruction Book.

299. As a first approximation, calculate the air gap value by means of Equation **21** of the Instruction Book, assuming that about 70% of the field ampere turns are wasted in the air and allowing a reduction of the calculated air gap of about 15% on account of the effective iron section being reduced by the slot openings, which consideration is entirely neglected by the application of the Formula **21.**

300. By means of Equation **26** of the Instruction Book, calculate the leakage factor of this synchronous motor and see whether the value thus obtained is in accordance with that assumed above.

301. Calculate 4 points of the no-load characteristic, for 1,000, 1,800, 2,200 and 2,500 volts and collect the different data in tabular form, similar to Table 19 of the Instruction Book. The path lengths which must be known for this purpose are to be taken from a full-sized sketch or may be calculated.

302. By means of Equation **29** of the Instruction Book, calculate the short circuit constant for this synchronous motor, determining first the reluctance of the armature leakage path. For this purpose take the projecting-out part of the armature winding as $2l_1 = 9$ inches.

303. The short circuit constant being calculated as $k_s = 1.16$, determine by means of Equation **15** of the Instruction Book the amount of field ampere turns per pole which correspond to the normal shortcircuit current of the armature.

304. Plot the no-load and short circuit characteristics of this synchronous motor, applying the following scales:

1,000 ampere turns per pole = 1 inch.
500 volts terminal pressure = 1 inch.
50 amperes short circuit current = 1 inch.

305. In the same figure determine graphically the V-characteristic and therefrom state the necessary amount of excitation ampere turns corresponding to the normal armature current of 61.8 amperes with a leading power factor of cos. $\varphi = .90$

306. Assuming a total winding depth of 1.4 inch and a thickness of about .25 inch for the metal bobbin together with its insulation on each side of the pole core, calculate as a first approximation the length of a mean turn of the field coils.

307. Taking into consideration a margin of about 10% in excitation, calculate for 255 volts excitation pressure the necessary conductor section of the field coils and choose the most suitable size of S. W. G.

308. Allowing for the maximum excitation a current density of 1600 amperes per square inch, calculate the maximum necessary excitation current and the number of turns per pole.

309. State the most suitable arrangement of the turns and make a sketch ½ full size of two adjacent pole pieces showing their respective windings. For this purpose assume that in the radial direction the total room taken up by the bobbin and end plates is about 1 inch.

310. Calculate the excitation loss corresponding to the full $\cos \varphi = .9$ load.

311. Calculate the warm armature resistance and determine the armature copper loss at full load.

312. Calculate the weight of the teeth and the iron losses in same.

313. Calculate the weight of the armature core and the iron losses in same.

314. By means of Equation **43** and Fig. 25 of the Instruction Book, calculate the efficiency, at full load, of this synchronous motor.

315. By means of Equation **41** of the Instruction Book, calculate the temperature rise on the field coils.

316. By means of Equation **40** of the Instruction Book, calculate the temperature rise on the armature.

317. By means of Equation **39** of the Instruction Book, calculate the output coefficient of this synchronous motor.

318. Collect in tabular form the different data of this synchronous motor.

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